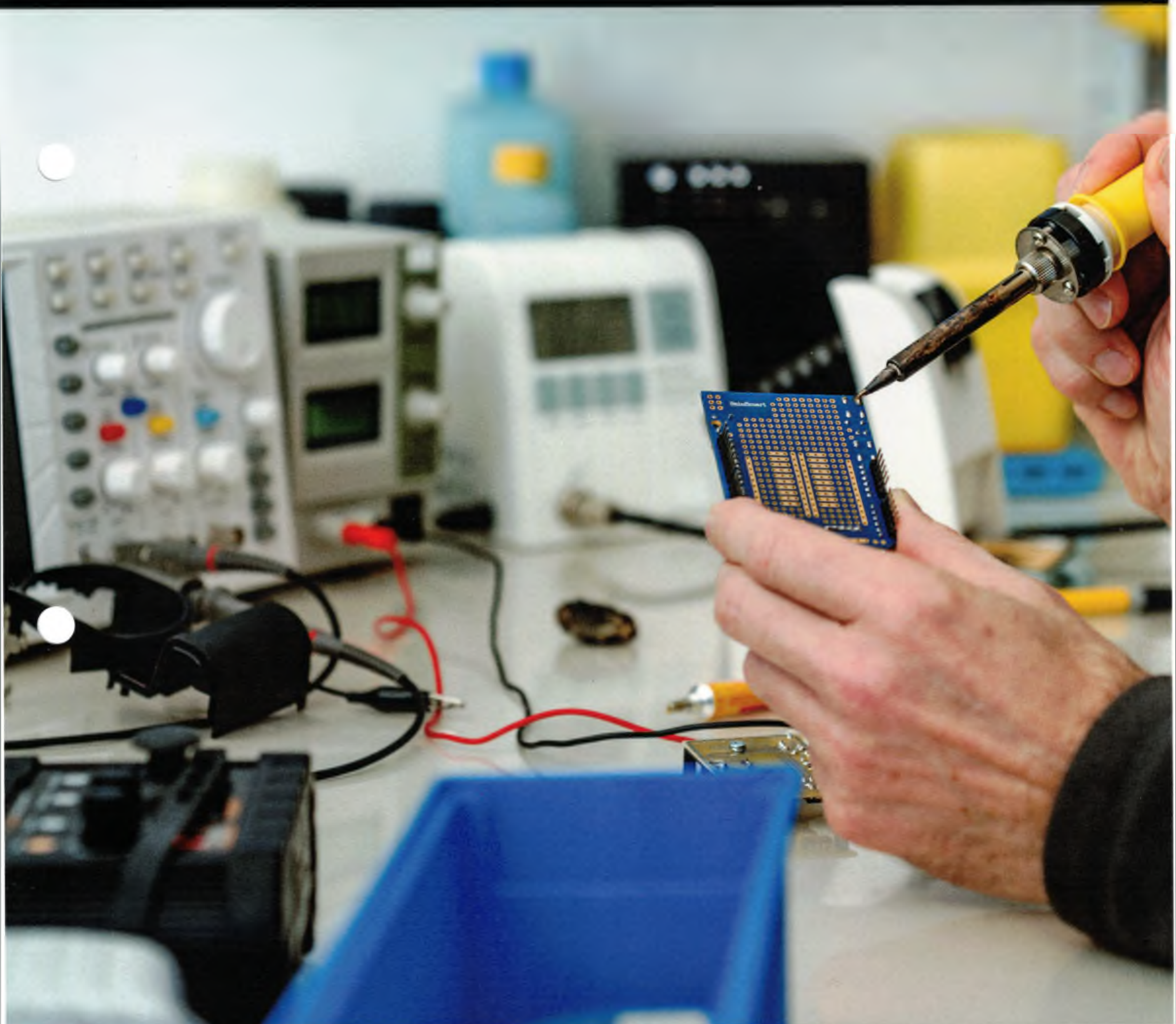
AC Principles and Applications Part 1



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Workbook

Contents

Introduction

This workbook is the first of two that have been written to help students satisfy the assessment requirements for the following Units:

- UEEEC0074 - Troubleshoot resonance circuits in an electronics apparatus

More information about electrotechnology training packages and the above Units can be found at www.training.gov.au/home/tga. Type the course/unit number in the "Quick search" and press return.

Textbooks

The following textbooks can be used to supplement the notes in this workbook. Most (if not all) of these books are available from the library in Building D.

- Batty (1997). *More Electrical Principles*. Prentice Hall.
- Boylestad & Nashelsky (2002). *Electronic Devices and Circuit Theory* (8th edition). Prentice Hall.
- Donovan (2002). *Electronics Mathematics* (2nd edition). Prentice Hall.
- Edwards & Myer (1993). *Electronics; a basic course* (2nd edition). McGraw Hill.
- Floyd (2002). *Electronic Devices* (6th edition). Prentice Hall.
- Gates (2001). *Introduction to electronics* (4th edition). Thompson Printing.
- Grob (1997). *Basic Electronics* (8th edition). McGraw Hill.
- Hazen (1991). *Exploring Electronic Devices*. Saunders Publishing.
- Ludeman (1990). *Electronic Devices and Circuits*, Saunders Publishing.
- Metzger (1998). *Electronics Pocket Handbook* (3rd edition). Prentice Hall.
- Paynter & Boydell (2002). *Electronics Technology Fundamentals*. Prentice Hall.
- Phillips (1997). *Electrical Principles 2*. Nelson Thompson Publishing.

Lesson organiser

The following is a suggestion only. It may be changed to meet student needs and/or different modes of delivery.

Lesson	Section	Topics and activities
Before starting (ideally)	Required reading	■ Work health and safety ■ Using sustainable energy practices ■ Communication and documentation ■ Test and measurement devices and their safe use
1	1	■ Inductors ■ Inductance ■ DC inductive circuits
2	2	■ Alternating voltages and currents ■ Practise measuring AC voltage and current using a DMM
3	3	■ Using the oscilloscope ■ Practise measuring DC and AC voltages and the period of AC waveforms using an oscilloscope
4	4	■ Phase ■ Measuring phase difference ■ Phasors ■ Practise measuring the voltage of, and the phase difference between, signals using an oscilloscope
5	5	■ The basic principles of transformer operation ■ Practise measuring primary and secondary voltages of a step-down and step-up transformer using an oscilloscope
6	6	■ **Possible assessment - Refer to the UAG for details** ■ Pure resistance in AC circuits ■ Practise measuring AC voltages and currents in series and parallel resistive circuits using a DMM and an oscilloscope
7	7	■ Inductive and capacitive reactance ■ Practise measuring AC voltages in series RL and RC circuits using an oscilloscope
8	8	■ Impedance ■ Practise measuring AC voltages in series RL, RC and RLC circuits using an oscilloscope
9	9	■ Calculating voltages and currents around RL, RC and RLC circuits ■ Practise measuring AC voltages in series RL, RC and RLC circuits using an oscilloscope
10	10	■ **Possible assessment - Refer to the UAG for details** ■ Power in AC circuits with reactive components

Lesson	Section	Topics and activities
11	Pt 2 - 1	■ **Possible assessment - Refer to the UAG for details** ■ Complex waveforms and an introduction to the spectrum analyser
12	Pt 2 - 2	■ An introduction to filters ■ Practise identifying filter responses using the oscilloscope
13	Pt 2 - 3	■ Filter performance characteristics ■ Practise determining the frequency performance of a loudspeaker crossover using the oscilloscope
14	Pt 2 - 4	■ Low-pass and high-pass filter circuits ■ Practise measuring the output voltage of, and the phase shift introduced by, LPFs and HPFs using an oscilloscope
15	Pt 2 - 5	■ Resonance ■ Practise measuring the voltage across components in resonant circuits using an oscilloscope
16	Pt 2 - 6	■ Band-pass and band-stop filter circuits ■ Practise measuring the output voltage of, and the phase shift introduced by, BPFs and BSFs using an oscilloscope
17	■ **Possible assessment - Refer to the UAG for details**	
18	■ **Possible assessment - Refer to the UAG for details**	

Note: The lesson notes for lessons 11 to 16 are in the workbook called *AC Principles & Applications - Part 2*. The lesson organiser for Part 2 is provided here to give you the full picture of what is to be taught in for this unit.

Required reading

Purpose

These notes are provided to support your revision on aspects of this Unit that have been taught before in other Units (typically more than once) and will not be taught again but may be assessed.

This issue is explained in more detail on the following pages.

Introduction

As you probably know, *units of competence* that make up qualifications in the Electrotechnology Training Package (like CIII Electronics and Communications) prescribe what must be taught and assessed.

This is done using *elements of competence* together with *performance criteria* for each element. More detail on these is provided in the *assessment requirements* for the unit using two lists: one is the list of *performance evidence*; and the other is the list of *knowledge evidence*.

There are some performance criteria (together with performance evidence and/or knowledge evidence in the assessment requirements) that appear in many units and these include items on the following topics:

- work health and safety (WHS)
- using sustainable energy practices
- the appropriate use and completion of documentation
- appropriate communication with supervisors, customers and other stakeholders.

It makes sense that these performance criteria are common to multiple units because, taking WHS as an example, it's not reasonable to claim competence when the work was completed successfully but in an unsafe way.

As well as the topics listed above, there are performance criteria and/or assessment requirements related to electrical/electronic theory and practice that appear in two or more units. This occurs when the people who have developed the training package (not TAFE NSW) have decided that it's appropriate that they should do so. An example of this for UEEEC0074 is the requirement for you to demonstrate your knowledge of how to connect a digital multimeter to a circuit to measure potential difference which you have previously learnt about when undertaking CD0043 (formerly UEENEEE104A).

Importantly, where all these topics have been comprehensively taught before, it is usually unnecessary to teach them a second or third time. That said, we are still expected to ask you to provide knowledge evidence and/or performance evidence possibly by answering questions on these topics in the theory test and/or demonstrating your skills on these topics during the practical tests.

For this reason, the following information and/or notes are provided for you to read and use to ensure that you can satisfy the assessment requirements for this unit.

Work health and safety (WHS)

When you undertake the in-class simulated workplace tasks and/or the practical test for this unit (EC0074), you're expected to demonstrate your knowledge of, and demonstrate your ability to carry out, the following performance criteria related to WHS and their associated knowledge evidence and performance evidence:

1.1 - Work health and safety (WHS) processes and workplace procedures for a given work area are obtained and applied (UEECD0007 references: 1.2, 1.3 & 1.4)

1.2 - WHS risk control work preparation measures and workplace procedures are followed (UEECD0007 references: 1.2, 1.3 & 1.4)

2.1 - WHS risk control work measures and workplace procedures are followed (UEECD0007 references: 1.4, 1.6, 2.1 and 2.4)

2.2 - Need to test and measure live work is determined in accordance with WHS requirements and workplace procedures (UEECD0007 references: 1.2, 1.3 & 1.4)

3.1 - WHS risk control measures and workplace procedures are followed (UEECD0007 references: 3.1 to 3.4)

3.2 - Worksite is cleaned and made safe in accordance with workplace procedures (UEECD0007 references: 2.6)

Source: https://training.gov.au/Training/Details/UEEEC0074

As you may already be aware:

- WHS is taught and assessed in a dedicated unit, CD0007 (formerly E101A)
- CD0007 or E101A is a pre-requisite unit for undertaking EC0074 (that is, you must have successfully completed CD0007 or E101A to be able to undertake EC0074)
- The performance criteria listed above are underpinned by, and/or are identical in substance to, the performance criteria from CD0007 (and E101A) indicated in the brackets above

Importantly, the knowledge and skills needed to perform these performance criteria are identical to those needed to repair RL, RC and RLC circuits. This means that you already have the ability to demonstrate your knowledge of, and demonstrate your ability to carry out, these performance criteria in the context of this unit.

However, if your unsure and would like to read more information about these performance criteria, please refer to your learner resources for CD0007/E101A that specifically address them.

Note: If you have not successfully completed CD0007 or E101A, please bring this to the urgent attention of the teacher before undertaking any of the simulated workplace tasks.

Using sustainable energy practices

When you undertake the in-class simulated workplace tasks and/or the practical test for this unit (EC0074), you're expected to demonstrate your knowledge of, and demonstrate your ability to carry out, the following performance criterion:

2.6 - Fault-finding activities are carried out efficiently without waste of materials, or damage to apparatus, the surrounding environment or services using sustainable energy practices.

This includes knowing about sustainable energy principles and using sustainable energy practices.

Sustainability is a much used word now that describes growing global response to the short and long term negative effects on the planet of certain human activities, particularly in relation to climate change and pollution. It's accepted that, without drastic action, both problems will likely make living on this planet more difficult (due to extreme weather and toxic environments) that, in turn, risk causing drought, famine, war and the failure of democratic governments and even whole nation states.

R J Fuller (Deakin University, 2005) describes four principles that underpin sustainability:

- Futurity - The concern for future generations
- Environment - The concern to protect the integrity of eco-systems
- Equity - The concern for the poor and disadvantaged
- Participation - The notion that individuals can participate in decisions affecting them

An essential element of the global response to climate change is the switch to sustainable energy. Energy is said to be sustainable if it "meets the needs of the present without compromising the ability of future generations to meet their own needs." Underpinning this are the sustainable energy principles which include (but are not limited to):

- Reducing our use of non-renewable energy sources (like the fossils fuels which includes coal, gas and oil)
- Increasing our use of renewable sustainable energy sources (like solar just to name one of many)

Fuller's fourth principle is important because it means that individuals, including you, can contribute directly and indirectly to sustainable energy principles by using sustainable energy practices where possible. Direct action that can be taken includes (but is not limited to):

- Switching off equipment not in use
- Turning off lights when leaving a room with nobody in it
- Opening windows to cool rooms instead of turning on room air-conditioning
- Using natural lighting
- Minimising waste
- Recycling waste
- Using public transport to and from work
- Drinking tap water

Indirect action that can be taken, includes (but is not limited to) encouraging your employer to:

- Using more energy efficient lighting
- Using more energy efficient equipment
- Reducing (in winter) and increasing (in summer) the temperature setting of air conditioning so that to uses less energy
- Switching to using sustainably sourced and/or sustainably manufactured materials
- Switching to an SEU energy provider

With all that said, every workplace is different so what works with one may not work with another.

Communication and documentation

When you undertake the in-class simulated workplace tasks and/or the practical test for this unit (EC0074), you're expected to demonstrate your knowledge of, and demonstrate your ability to carry out, the following performance criteria related to workplace communication and documentation and their associated knowledge evidence and performance evidence:

1.3 - Scope of fault is obtained from documentation and/or work supervisor to determine the work to be undertaken

1.4 - Advice is sought from work supervisor to ensure work is coordinated effectively with others

1.5 - Sources of materials required for the work are determined in accordance with workplace procedures

1.6 - Tools, equipment and testing devices required for work are obtained and are checked for correct operation and safety.

3.3 - Work completion is documented and appropriate person/s notified in accordance with workplace procedures

The specific knowledge required to satisfy these performance criteria is specific to each workplace setting. However, the skills are generic and so are transferable between workplace settings including simulated workplace settings at TAFE NSW. This means that, when you undertake the in-class simulated workplace tasks and the practical test, you are expected to demonstrate your skills in this regard.

Importantly, while undertaking the in-class simulated workplace tasks and/or the practical tests for this unit at TAFE NSW, the following applies to key terms in the performance criteria above:

- "Work supervisor" refers to the class teacher
- "Others" refers to the class teacher and other students in the class
- "Materials" refers to components and training aids needed to carry out the simulated workplace tasks as described in the skill practise exercises' equipment list
- "Workplace procedures" refer to the written and verbal procedures and instructions provided by the teacher for the safe and proper conduct of skill practise exercises
- "Tools, equipment and testing devices" refers to tools and test equipment needed to carry out the simulated workplace tasks as described in the skill practise exercises' equipment list and/or mounted on the workbenches
- "Documented... in accordance with workplace procedures" refers to the requirement for students to record their measurements, other results, and answers to questions on the skill practice exercises and/or any handouts that must be submitted to the teacher.

The following is the procedural requirement for undertaking the simulated workplace tasks that form the basis of skill practise exercises.

- Students must have permission from the teacher to start every skill practice exercise.
- Students must work individually on every skill practise exercise, or in pairs with the permission of the teacher (but never more than two per group).
- Students must perform a WHS risk assessment at the start of every skill practice exercise to ensure the safety of themselves and others.
- Students are to bring to the attention of the teacher any hazards that they identify for which there are they cannot implement appropriate control measures.
- Students are to collect equipment from the trolley in a safe and orderly manner having respect for the reasonable needs of other students.
- Students are to follow the written instructions in every skill practice exercises in correct order and in total including any qualifying notes.
- Students are expected to record their measurements, other results and answers to questions for every skill practice exercise and/or any handouts that must be submitted to the teacher.
- Students are expected to call the teacher to check their work when instructions direct them to do so.
- Students are expected to retake any measurements and reattempt and/or correct any of their answers to questions when reasonably directed to do so by the teacher.
- Students are not to return their equipment to the trolley or leave **until** they have completed the skill practice exercise and their work has been checked by the teacher.
- Students are expected to submit their work to the teacher by the due date when required to do so.
- At the completion of every skill practice exercise, students are expected to return all equipment to the trolley tidily (unless directed otherwise by the teacher) and ensure that the workspace is left cleaned and safe.
- Students are to bring to the attention of the teacher any faulty test equipment, tools and components.

Test and measurement devices and their safe use

When you undertake the in-class simulated workplace tasks and/or the practical test for this unit (EC0074), you're expected to demonstrate your knowledge of:

- Electronic testing and measuring devices and techniques including:
  - test/measuring devices and their application including:
    - multimeters
    - function generators
    - oscilloscopes
  - connection of test/measruing devices into a circuit including:
    - ensuring circuits are isolated
    - testing or measuring on live and operating system safely
    - circuit arrangement of test/measuring devices

You first learnt about multimeters and practised using them on live circuits when undertaking unit CD0043. There are a couple of minor differences when using multimeters for testing AC circuits and these will be explained in the appropriate lesson in this unit. (You haven't learnt about function generators and oscilloscopes yet and much of this unit will teach you about these instruments and give you many opportunities to practise using them.)

Importantly, you're expected to know the general principles of using multimeters and the safety precautions around working on live circuits. However, if your unsure that you are able to demonstrate your knowledge of these tasks or your ability to carry them out, the following notes have been provided here for your convenience for you to read.

Safety considerations when connecting test and measurement devices to circuits
When using a multimeter or oscilloscope to test and measure electronics equipment, there are two important safety measures that can minimise the risk of your being fatally electrocuted.

The first relates to the fact that technicians usually must necessarily test mains-operated electronics equipment (like a hi-fi or PVR) that is plugged-in, turned on and operating. To minimise the risk of electrocution, you must ensure that the equipment that you're testing or repairing is plugged into a power point that is protected at the switchboard by a residual current device (RCD). You can check whether the building's powerpoints are RCD protected by looking inside the switchboard. Figure 1 below shows an example of what to look for.

Figure 1

Up close, RCDs look like the example in Figure 2 below and there should be at least one row of these devices in the switchboard mounted side-by-side. RCDs are easily recognised by the fact that they're switched devices and often they have an in-built test feature too.

Figure 2

RCDs have been designed expressly for the purpose of preventing people and animals from a sustained direct connection to mains which can be fatal.

If the switchboard is older it may use semi-enclosed cartridge fuses instead of RCDs and an example is shown in Figure 3 below. Importantly, being fuses, these devices are designed to protect equipment and prevent fires but they **do not** prevent people/animals from potentially fatal electrocution. You should avoid powering the equipment that you're testing/reparing from power points that are only protected at the switchboard by these fuses.

Figure 3

If you can't access the switchboard to see what's inside, or you know for certain that the power point is not RCD protected, then plug the equipment that you're testing into the powerpoint of a powerboard that is RCD protected instead. An example is shown in Figure 4 below - Notice the RCD at the left end (which includes a button for the test feature).

Figure 4

Take care when purchasing protected powerboards because there are many that offer "surge" and/or "overload" protection. While these features are useful, they don't provide protection from electrocution. Powerboards that are RCD protected will state this clearly and are usually a fair bit more expensive than simple surge and overload protected powerboards.

The second safety measure you must employ when connecting multimeters to live equipment, involves never doing so with your fingers touching any of the probe's metal parts. Figure 5 below shows the correct way to hold the probes. Notice that the person holds the probes behind the their slip barriers.

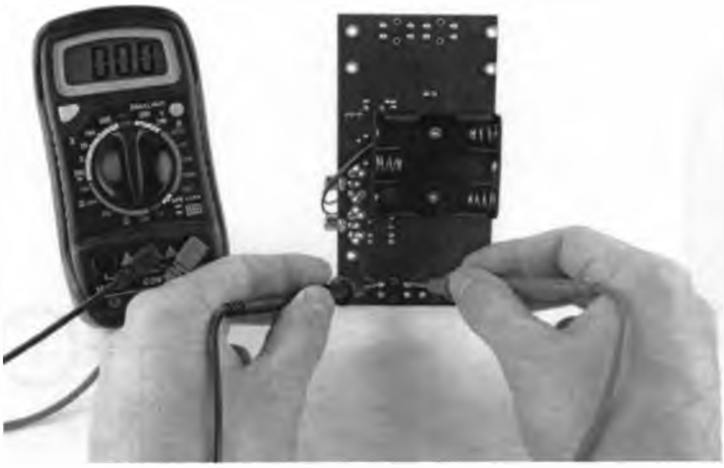


Figure 5

The correct connection of test and measurement devices to circuits

When measuring DC potential differences, the voltmeter is connected to the circuit in parallel with the component whose potential difference you want to measure. This is shown in Figure 6 below using a simple series circuit consisting of a resistor and a lamp with the meter measuring the DC potential difference across the resistor. The meter is shown both as a drawing (on the left) and as a schematic symbol (on the right).

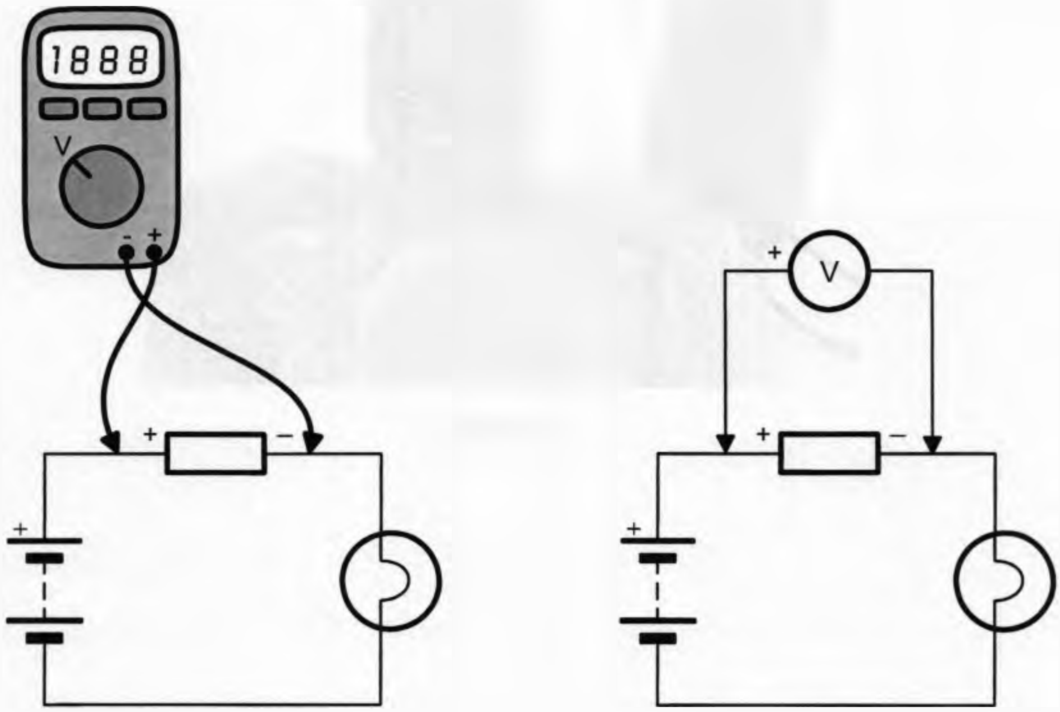


Figure 6

Notice that the voltmeter's positive probe must be connected to a DC potential difference's positive side. Importantly, although the electrical connection of the voltmeter is identical for measuring the potential difference in AC circuits (ie it's a parallel connection), you don't have to worry about which probe connects to which side of the component. This is because the direction of current is alternating (that is, it travels one way around the circuit for a time then reverses direction travelling the other way around the circuit for a time) and so the polarity of the potential difference (ie the voltage) is alternating too. For the instrument to cope with this, you must choose the multimeter's AC voltage measuring mode instead of its DC voltage measuring mode.

Care must be taken when connecting the meter to the circuit so that you don't actually short two points of the circuit together.

When measuring currents, the ammeter is connected to the circuit in series with the component whose current you want to measure. This is shown in Figure 7 below using a simple series circuit consisting of a resistor and a lamp with the meter measuring the current through the resistor (which is also the current through the lamp in this case because it's a series circuit). The meter is shown both as a drawing (on the left) and as a schematic symbol (on the right).

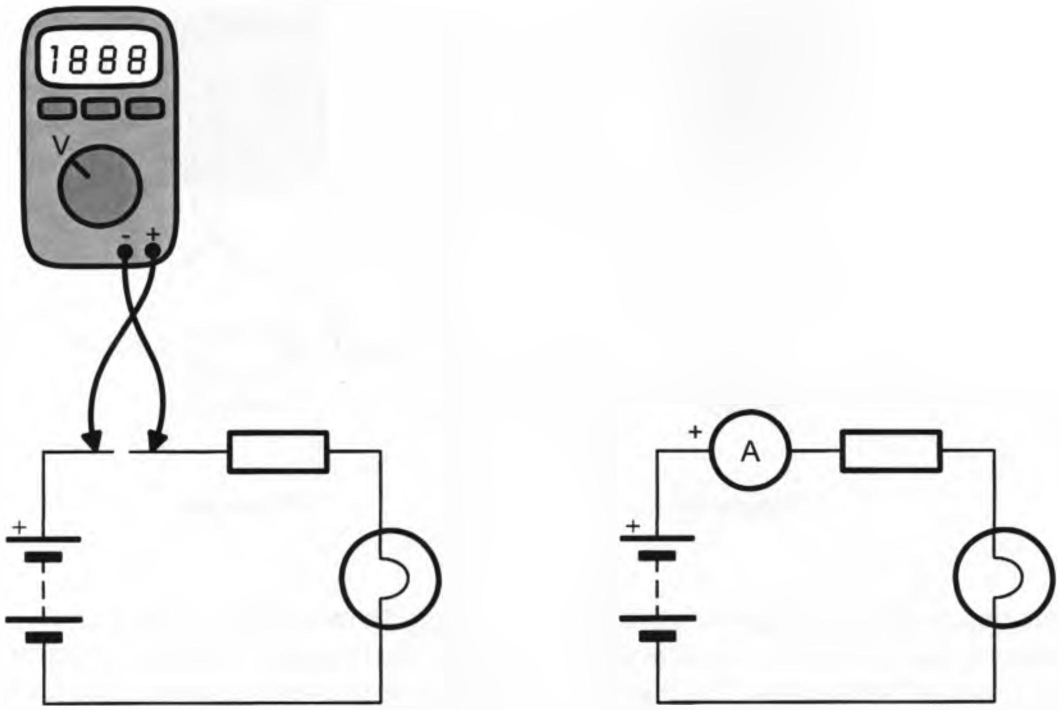


Figure 7

Notice that the circuit must be broken at some point to introduce the ammeter (an inconvenience that limits the practical measurement of current in the workplace). And, just like with AC voltage measurements, you don't have to worry about which probe to connect to which side of the break in the circuit. But you must choose the multimeter's AC current measuring mode instead of its DC current measuring mode.

Measuring resistance of resistors is a simple matter of connecting the meter's probes across the component in any polarity as shown in Figures 8 below. Importantly though, recall that the component should be removed from the circuit before you make the measurement.

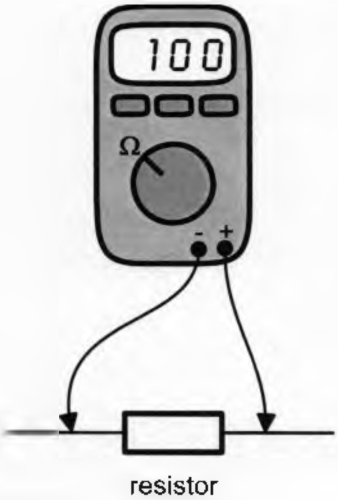


Figure 8a

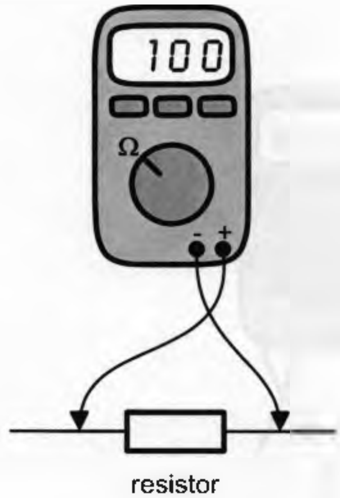


Figure 8b

Also remember that your fingers should not be touching the metal parts of the probes. If the component is out of the circuit, you're not going to get electrocuted. However, if you're touching the metal parts of both probes, the ohmmeter may show an incorrect resistance for the component because the measurement will include your bodily resistance.

Section 1 Inductors, inductance and DC inductive circuits

Purpose

To develop an understanding of the factors that affect inductance and develop the ability to identify inductor characteristics and specifications relevant to repair technicians.

Objectives

At the end of this section you should be able to:

- Describe the construction of the basic inductor
- State two other commonly used names for the inductor
- Draw the Australian standard schematic symbols for fixed and variable inductors
- Explain how the inductor stores energy as an electromagnetic field
- Define inductance and give its symbol
- State the unit of measurement for inductance and give its symbol
- List the factors that affect the inductance of an inductor
- Calculate the value of an inductor given its physical dimensions and the permeability of the core
- List typical applications for inductors in electronic circuits
- List examples of where the inductive effect occurs unintentionally
- Recognise common commercially available inductors
- Draw the graph of the energising and de-energising characteristic for an inductor in single-source DC series RL circuits
- Calculate the time constant of series RL circuits
- Calculate the total time it takes to energise and de-energise an inductor in a single-source DC series RL circuit
- Calculate instantaneous values of voltage and current in a single-source DC series RL circuit using a universal time constant chart

Introduction

In some respects, this lesson is out of place here. It introduces you for the first time in this course to the inductor. In the process, the basic operation of the inductor is discussed but using DC not AC circuits. However, there's method in the madness! You'll be learning about the operation of inductors in AC circuits later in this subject and a good understanding of how they work in DC circuits is essential.

The basic construction of an inductor

In its most basic form, the physical construction of an inductor is just a tightly coiled length of insulated wire. For this reason, the inductor is often called a *coil* (another common name for the inductor is *choke* because of how it reacts to changes in current through it).

The wire is usually copper and is usually insulated using a resin (rather than a plastic like PVC) which gives the wire a rusty red/brown colour. Examples of a simple inductor are shown in Figure 1 below which is a photograph of a *passive crossover*, a device found in the back of most speaker boxes.

Figure 1 *A passive crossover which has two inductors mounted on it*

The hole in the centre of an inductor is called the *core* and it can be left as it is - giving it an *air-core* - or it can be filled with a material that is better conductor of electromagnetic energy such as soft-iron or *ferrite*. Ferrite is a manufactured material made of powdered ceramic mixed with magnetic materials (such as iron-oxide) that is pressed and heated (*sintered*) to turn it into a solid in any desired shape.

Schematic symbol

The schematic symbol used for the inductor reflects its construction and is shown in Figure 2 below.

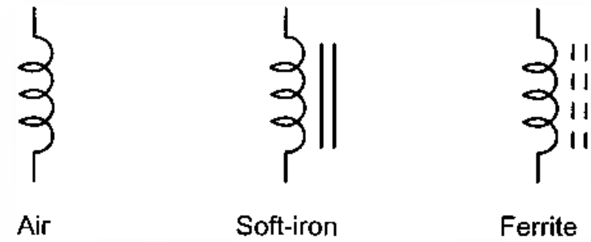


Figure 2 *The schematic symbol for the air-cored, soft-iron-cored and ferrite-cored inductors*

Variable inductors are also used in electronics equipment though much less often than variable resistors. Figure 3 below shows variable versions of the soft-iron and ferrite inductors.

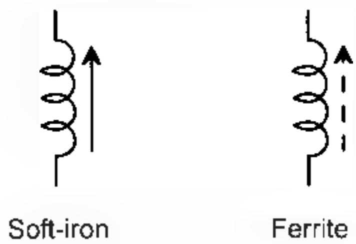


Figure 3 *The schematic symbols for variable inductors*

What do inductors do?

Put simply, inductors convert electrical energy to electromagnetic energy and store it. To explain, recall that when an electrical current flows through a conductor an electromagnetic field is developed about its entire length. This is shown in Figure 4 below.

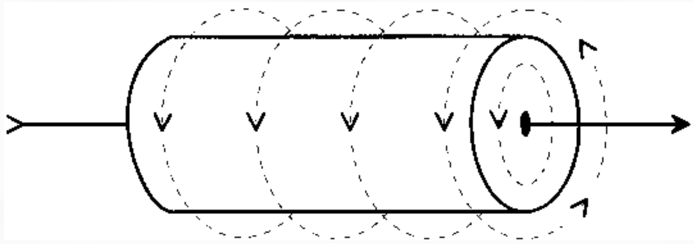


Figure 4 *The electromagnetic field about a conductor*

As the current begins to flow, the electromagnetic field expands outward from the conductor's centre reaching maximum and becoming static when the current reaches maximum. If the current through the conductor goes down, the field shrinks. If the current drops to zero, the electromagnetic field collapses altogether. As the field shrinks or collapses, stored energy is returned to the circuit in the form of electrical current.

As you know, inductors are simply coiled wire and so they behave in the same way. However, the intensity of electromagnetic energy is much bigger because all the energy along the wire's length is concentrated into a small area.

Inductance

Although the ability of inductors to generate and store electromagnetic energy is useful, they exhibit another property called *inductance* (L) that is equally important. Inductance is the opposition to changes in current through a conductor.

To explain, when an electromagnetic field expands out from the centre of a conductor or collapses toward it, the direction of the moving field is at right-angles (perpendicular) to the conductor. This is significant because, if a magnetic field of any sort is moved perpendicular to a conductor, a current is generated in the conductor.

Importantly, Heinrich Lenz (a Russian physicist of German descent) discovered that this second current wants to flow in the opposite direction to the current that caused the electromagnetic field in the first instance. As current can't flow through a conductor in two directions at once, the current generated by the electromagnetic field never really gets to flow. However, it does slow down any changes in current that cause an expansion or contraction of the electromagnetic field.

In other words, as current increases or decreases in any conductor, the resulting expansion or contraction of the electromagnetic field induces a current back into the wire that opposes the original change of current. This is like the struggle a wave has when it breaks on a beach. The wave rushes up the sand but has to push against the water running back into the sea from the previous wave.

If you look up this effect in textbooks, you'll find that there are several different ways of describing it, all of which are called Lenz's law. One of them refers to an idea called *back emf*. The back emf is the potential difference that is developed across the conductor by the induced current. It's called an "emf" because it's a voltage generated by the conversion of another form of energy into electrical energy. It's called "back" emf because the induced current wants to flow in the opposite direction to the actual circuit current, so the induced emf has the opposite polarity to the EMF that caused the circuit current.

The unit of measurement of inductance is the *Henry* (named after Joseph Henry, a US physicist born in 1797). The symbol for the Henry is (H). One Henry is said to exist when a change of one amp per second induces a back emf of one volt.

As inductors are made from conductors they also exhibit inductance but much more of it because the electromagnetic field is concentrated in a small area. In fact, inductors are very good at blocking changes in current through themselves and so they're often called *chokes*.

What are inductors used for?

There are many uses for inductors which can be grouped depending on which part of their operation you consider. For example, as we know, coils generate an electromagnetic field. This magnetic field is identical to that produced by a permanent bar-magnet and this is shown in Figure 5 below.

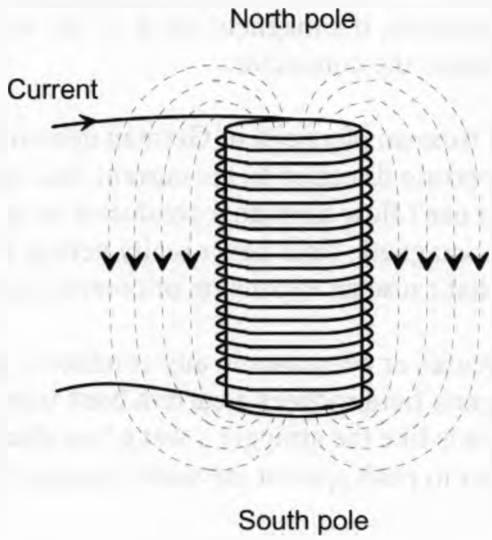


Figure 5 *The electromagnetic field about an inductor is the same as the magnetic field about a bar magnet*

That being the case, coils are ideal for use as magnets that can be turned on or off at will (or *electromagnets*).

Electromagnets are used inside relays to open or close switches using electrical signals. They're also used as *solenoids* which are coils with a spring-loaded magnetised core. When the coil is *energised*, the core either pops in or out (depending on how it has been designed) and when de-energised the spring makes the core return to its default position. Solenoids are used extensively for electronic *access control* (that is, electronic control of doors into and within buildings). Typing a security code into a keypad or swiping a card activates a solenoid near the door's lock for a short time and allows the door to be opened. Solenoids are also used to force a car's starter-motor to engage and turn the motor over when you turn the ignition key. When you let go of the ignition key, the solenoid is de-energised and the starter-motor disengages from the motor.

Another piece of equipment that uses an electromagnet is the speaker. The interaction between an electromagnet and a fixed permanent magnet is the basis of the operation of most speakers.

In terms of the fact that inductors store of electromagnetic energy, they can be used as an energy reservoir like capacitors are. However, all the stored energy is released back into the circuit very quickly after the inductor is de-energised so they're used for different applications to capacitors. An example is the *voltage recovery* circuit in a switched-mode power supply. You'll learn about these power supplies in a later subject.

Although these are all common and useful applications for inductors, what makes them so important to most electronics circuits is their inductance. As inductors oppose changes in current, they can be used to protect electronics equipment from *surges* on mains (like VDRs can do but in a different way). They can also be used together with capacitors to make filters and oscillators which are very important circuits in communications equipment such as radio and television. You'll learn much more about these circuits in this subject.

Another application for the inductor that relies on its inductance is the sensor used to detect when a car is waiting at a set of traffic lights. The sensor is just a loop of wire buried into the road just in front of the lights. There's usually one in each lane and if you look closely you can see the square-shaped scars where they've been covered over. The electronics that the loop is connected to gauge its inductance and look for a change. Without a car, the inductive loop's core is effectively air and so its inductance is small. However, when a car stops directly over the loop its core is replaced by metal which is a much better conductor of electromagnetic energy. This dramatically increases the loop's inductance and the electronics circuitry detects the change and responds to it accordingly.

Unintentional inductance

Although the inductor is a device that has been intentionally designed to make use of inductance, inductance occurs whenever current flowing through any conductor changes. Examples can include PCB tracks and cables used to join circuit boards. Fortunately, the inductance of these conductors in most applications is likely to be so small that it can be ignored. However, where it does start to become a problem is RF communications equipment but you'll learn more about this later in the course.

The physical factors that affect the inductance of an inductor

There are four physical factors that affect the inductance of an inductor. These are:

- the number of windings;
- the permeability of the core;
- the length of the coil; and
- the cross-sectional area of the windings.

To understand why the first three factors affect inductance you need to be clear about the relationship between the flux density of the electromagnetic field about a conductor/inductor and its inductance.

Recall that a changing current through a wire produces an expanding or contracting electromagnetic field. This moving field induces a current back in to the wire that opposes the change in current that caused the field to expand or contract in the first place. This is inductance.

Importantly, the amount of current induced back into the wire is proportional to the electromagnetic field's flux density. The greater the flux density, the greater the induced current. And, as we know, the greater the induced current, the greater the opposition to the original current (or inductance). Clearly then, inductance is directly related to the flux density of the electromagnetic field about the inductor and so the factors that affect flux density also affect inductance.

With that point made, let's consider how each of the physical factors that affect inductance does so.

The number of windings

A single loop of wire that conducts a certain amount of current will generate electromagnetic energy with a certain flux density. It logically follows that a bigger flux density of electromagnetic energy is developed about two or more adjacent loops.

That being the case, as an inductor is simply a series of adjacent loops (created by turning the wire around a core) its inductance is proportional its number of turns.

However, instead of the two being directly proportional, the relationship is a *square-law* function. That is, if you double the number of loops, the flux density increases by a factor of four. To put the reason for this simply, as the loops are wound next to each other, each loop is affected by its own moving electromagnetic field and the moving electromagnetic field from the adjacent loop or loops.

So, if the inductor has one loop it is only affected by only by its own electromagnetic field. However, if the inductor has two loops, the first loop is affected by its own electromagnetic field and the field about the second loop. At the same time, the second loop is affected by its own electromagnetic field and the field about the first loop. So, there are four interactions between conductor and electromagnetic field for only an increase from one loop to two.

Permeability of the core

It has been found that the flux density of electromagnetic field is affected by the physical properties of whatever it flows through in the same way that electrical current through a conductor is affected by the conductor's physical properties.

To explain, as you already know, the amount of current that flows through a conductor is affected by its resistance. The smaller the conductor's resistance, the bigger the current through it. And, the bigger the conductor's resistance, the smaller the current. Conductance is the exact opposite of resistance and so this relationship can be put in terms of the conductor's conductance instead. In which case, if the conductor's conductance is high, the current is high. If the conductance is low, the current is low.

Materials that conduct electromagnetic flux show a resistive/conductive effect too. These effects cannot be called resistance and conductance though because those two terms are already taken. Instead, resistance to electromagnetic flux is called *reluctance* and conductance of electromagnetic flux is called *permeability*.

The flux density of a field through a material is affected by how permeable the material is to electromagnetic fields. If the material's permeability is high, the field's flux density is relatively high. And, if the permeability is low, the flux density is relatively low.

That being the case, the inductance of an inductor is directly proportional to the core's permeability.

The length of the coil

As you know, the longer the length of a conductor, the greater its overall resistance. And, the greater the resistance, the smaller the current. The same is true for materials that conduct electromagnetic flux. The longer the path from the inductor's north pole to its south pole, the greater the reluctance and so the lower the flux density.

That being the case, the inductance of an inductor is inversely proportional to the inductor's length.

Cross-sectional area of the windings

Inside the core there is a conflict between the expanding field from opposite sides of any part of the loop. As they expand, they meet each other at the centre of the core and, as like-poles of an electromagnetic field oppose each other, the fields limit each other's expansion. This reduces the amount of flux that cuts across the conductor which in turn reduces the amount of induced current back into the wire.

The greater the cross-sectional area of the loop, the less the fields from opposing sides of any point in the loop interfere with each other's expansion and so the greater the inductor's inductance. As a result, the inductance of an inductor is directly proportional to the inductor's cross-sectional area.

Calculating inductance from physical properties - Not tested for CII & CIII

It is sometimes useful to be able to calculate an inductor's inductance if we know its physical dimensions. (That said, this is not common practice so you'll not be asked to do so in the exams for this subject. The notes on this page are provided for your interest.)

As the inductance of an inductor is related to the flux density of the electromagnetic field about it, if the number of loops is known as well as their cross-sectional area, the core's permeability and the coil's length, the inductance of the inductor can be calculated. The equation for this is:

$$\boxed{L = \frac{N^2 \times a \times \mu}{l}}$$

Where:
L is the inductance
N is the number of turns
a is the cross-sectional area of the core
µ is the permeability of the core (given)
l is the length of the coil

Note: This equation has a limited accuracy due to factors not discussed here.

To demonstrate how to use the equation let's do an example. What is the inductance of a 50mm long inductor that has 1000 turns at a diameter 5mm and has only air for the core? The permeability (µ) of air is 1.26×10^{-6} H/m.

First we must calculate the cross-sectional area of the windings:

$$a = \frac{\pi \times d^2}{4} \quad \text{or} \quad a = \pi \times r^2$$

$$a = \frac{\pi \times 0.005^2}{4} \qquad a = \pi \times 0.0025^2$$

$$a = 19.63 \times 10^{-6} m^2 \qquad a = 19.63 \times 10^{-6} m^2$$

Now we can calculate the inductance:

$$L = \frac{N^2 \times a \times \mu}{l}$$

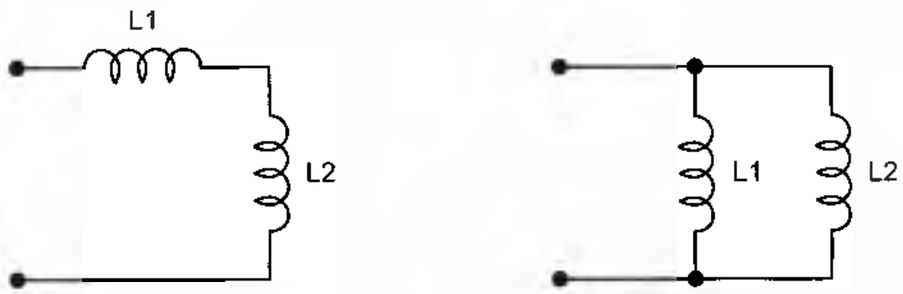
$$L = \frac{1000^2 \times 19.63 \times 10^{-6} \times 1.26 \times 10^{-6}}{0.05}$$

$$L = 494.7 \mu H$$

Inductors connected in series and parallel

For a variety of practical reasons, it is much less common to wire inductors either in series or parallel than it is to do the same with resistors and capacitors. Where it is done, we're often not very interested in the total inductance because of the other components in the circuit.

However, if you need to calculate the total inductance of series or parallel inductors the equations are identical to calculating the total resistance or resistors connected in series or parallel. This is shown in Figure 6 below.



$$L_T = L1 + L2$$

$$L_T = \frac{1}{\frac{1}{L1}+\frac{1}{L2}}$$

Figure 6 *Calculating the total inductance of series and parallel inductive circuits*

RL circuits

As you have learnt, inductors oppose changes in current. This means that when an inductor is energised the current that ultimately flows (called the *steady-state* current) takes a certain amount of time to build up. Similarly, when the inductor is de-energised the circuit current takes a certain amount of time to drop to zero.

Importantly, the rate of the current's change is exponential in both cases in the same way as for capacitors in RC circuits. Moreover, if a resistor is connected in series with an inductor (making an RL circuit) the rate of change speeds up (which is the opposite to RC circuits!).

Let's consider what happens in an RL circuit more closely.

Energising the inductor in an RL circuit

Figure 7 below shows an RL circuit connected to an EMF via a switch. The switch is in position B so the inductor is fully de-energised. In this condition, the circuit current is 0A and the potential difference across both components is 0V.

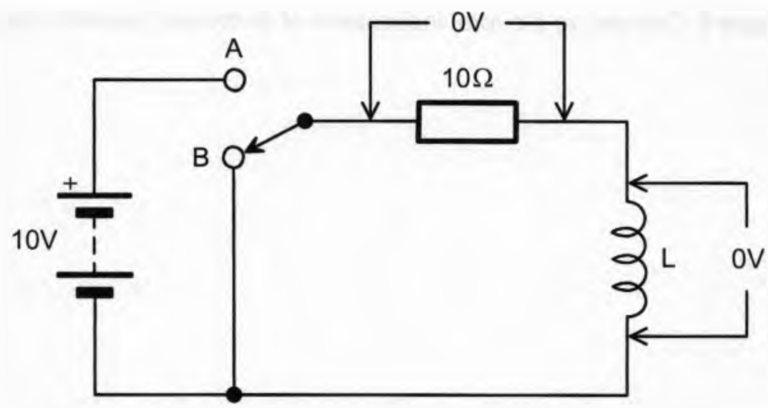


Figure 7 *The conditions around an RL circuit in which the inductor is de-energised*

When the switch is moved to position A, the EMF is connected to the circuit so current flows as shown in Figure 8. This current begins to energise the inductor.

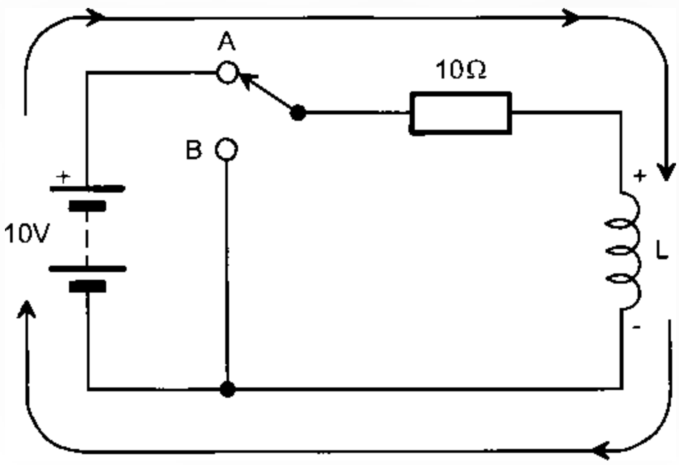


Figure 8 *The (conventional) current around the circuit when the inductor is connected to the EMF and begins to energise*

Assuming an ideal inductor (that is, the inductor has no resistance) the steady-state current is determined by the value of resistor and the EMF which, in this example, is ($I = \frac{10V}{10\Omega}$) 1A. However, as already mentioned, the current doesn't reach that value instantly. It takes time to build up and the rate of change is exponential as shown in Figure 9 below.

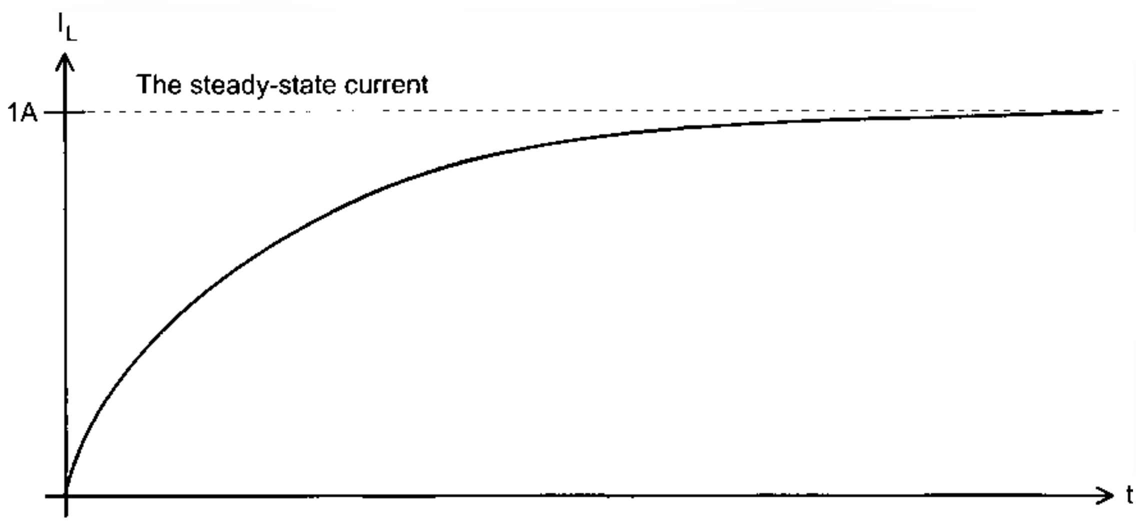


Figure 9 *When an inductor is energised the circuit current builds up exponentially toward the steady-state current which is 1A in this example*

As the circuit current rises towards the steady state current, there are corresponding changes in potential differences around the circuit. These changes are as follows:

At the instant that the switch is thrown to position A, the circuit current is 0A. As you know, Ohm's Law dictates that the potential difference across any resistor is directly proportional to the current through it. So, when the circuit current is 0A, the potential difference across the resistor is 0V. At the same time, Kirchhoff's Voltage Law (KVL) dictates that the sum of the potential differences around the circuit must equal the EMF so the potential difference across the inductor jumps up to the EMF voltage (10V in this example).

Then, as the circuit current rises exponentially, the potential difference across the resistor rises exponentially also. At the same time, due to KVL, the potential difference across the inductor falls exponentially.

If the inductor is ideal then, once the circuit current reaches the steady-state current and stops changing, the potential difference across the inductor is 0V. At the same time, the potential difference across the resistor is equal to the EMF.

The final circuit current and distribution of potential differences around the circuit are shown in Figure 10 below.

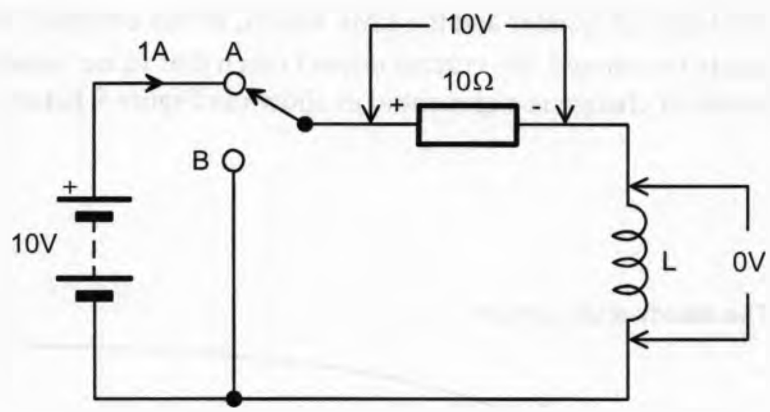


Figure 10 *The conditions around an RL circuit in which the inductor is fully energised*

These changes in potential difference across the components are shown as graphs time-coincident with the graph of circuit current in Figure 11 on the next page.

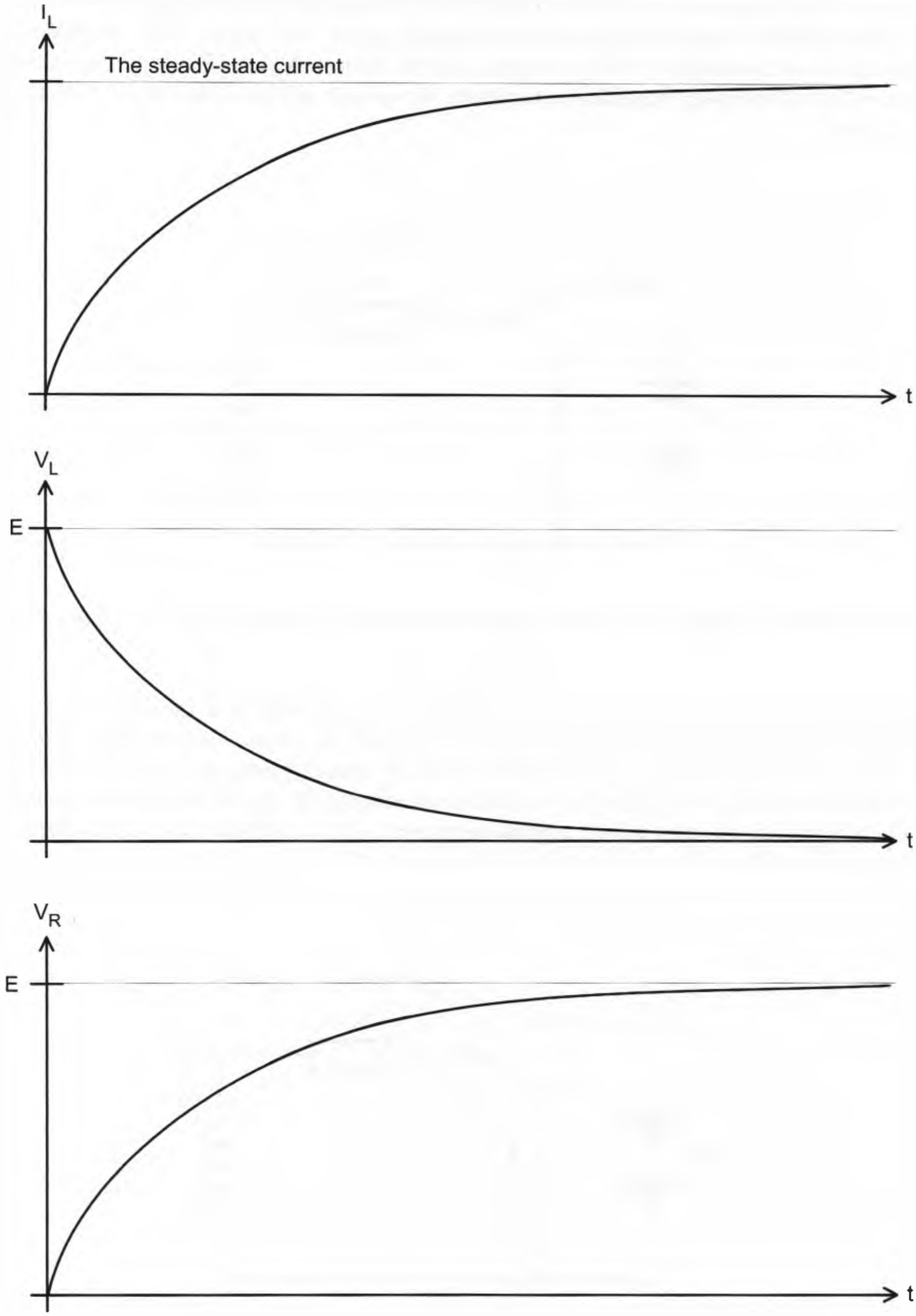


Figure 11 *The graphs of circuit current and potential differences in an RL circuit as the inductor energises*

De-energising the inductor in an RL circuit

To explain what happens around an RL circuit when the inductor is de-energised, we'll continue to use the example of an RL circuit with a 10V supply and a 10Ω resistor. The conditions around the circuit when the inductor is fully energised are reshown in Figure 12 below. The steady state current is 1A and the potential differences across the resistor and the inductor are 10V and 0V respectively.

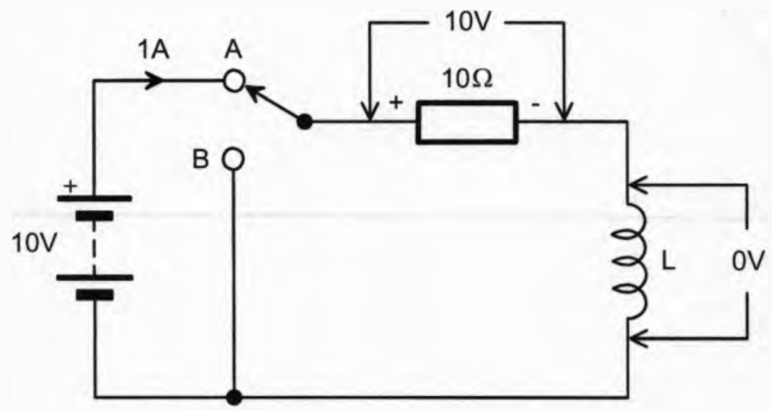


Figure 12 *The conditions around the circuit of an RL circuit in which the inductor is fully energised*

When the switch is thrown to position B, the EMF is disconnected from the circuit and no-longer provides a source of electrical current. When this happens the circuit current wants to drop to a new steady-state value of 0A. Ordinarily this would be instantaneous. However, the collapsing electromagnetic field about the inductor induces a current back into the wire that opposes the circuit current's fall. In other words, current continues to flow in the circuit even though the EMF has been disconnected. This is shown in Figure 13 below.

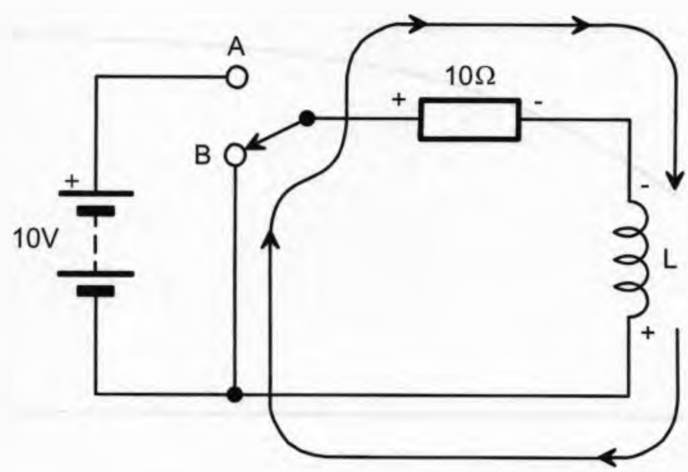


Figure 13 *The current around the circuit as the inductor de-energises*

At first glance, the potential difference across the inductor in Figure 13 looks wrong. However, it must be remembered that as the inductor de-energises it becomes a source of EMF rather than just another component and, as we know, conventional current flows from the positive terminal of an EMF to the negative terminal. That being the case, the polarity of the potential difference across the inductor is correct.

At the instant that the switch is thrown to position B the circuit current momentarily remains 1A. This means that the potential difference across the resistor momentarily remains 10V. The source of the potential difference developed across the resistor is the inductor which is now acting as an EMF. That being the case, the potential difference across the inductor is also momentarily 10V. These circuit conditions are shown in Figure 14 below.

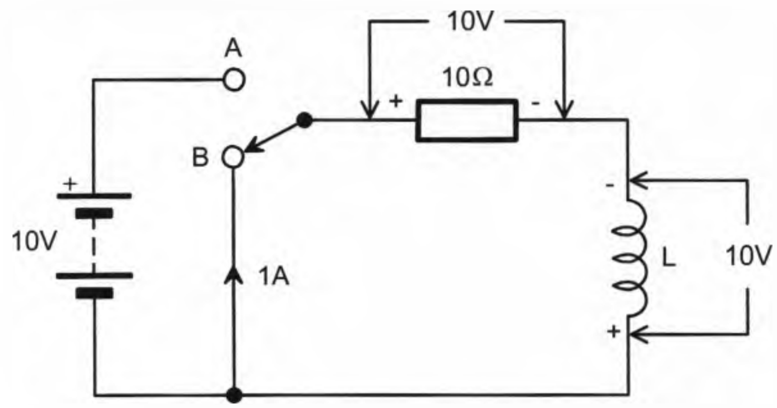


Figure 14 *The potential differences around the circuit the moment the switch the thrown to position B*

As the electromagnetic field about the inductor continues to collapse the circuit current goes down and so does the potential difference across both the inductor and the resistor. Ultimately, the field about the inductor collapses completely so the current drops to 0A and the potential differences across the resistor and inductor drop to 0V. In this condition, the circuit is identical to the one we started with in Figure 7 on page 1-12.

These changes in circuit current and potential difference across the components are all exponential and are shown as graphs time-coincident with the graph of circuit current in Figure 15 on the next page.

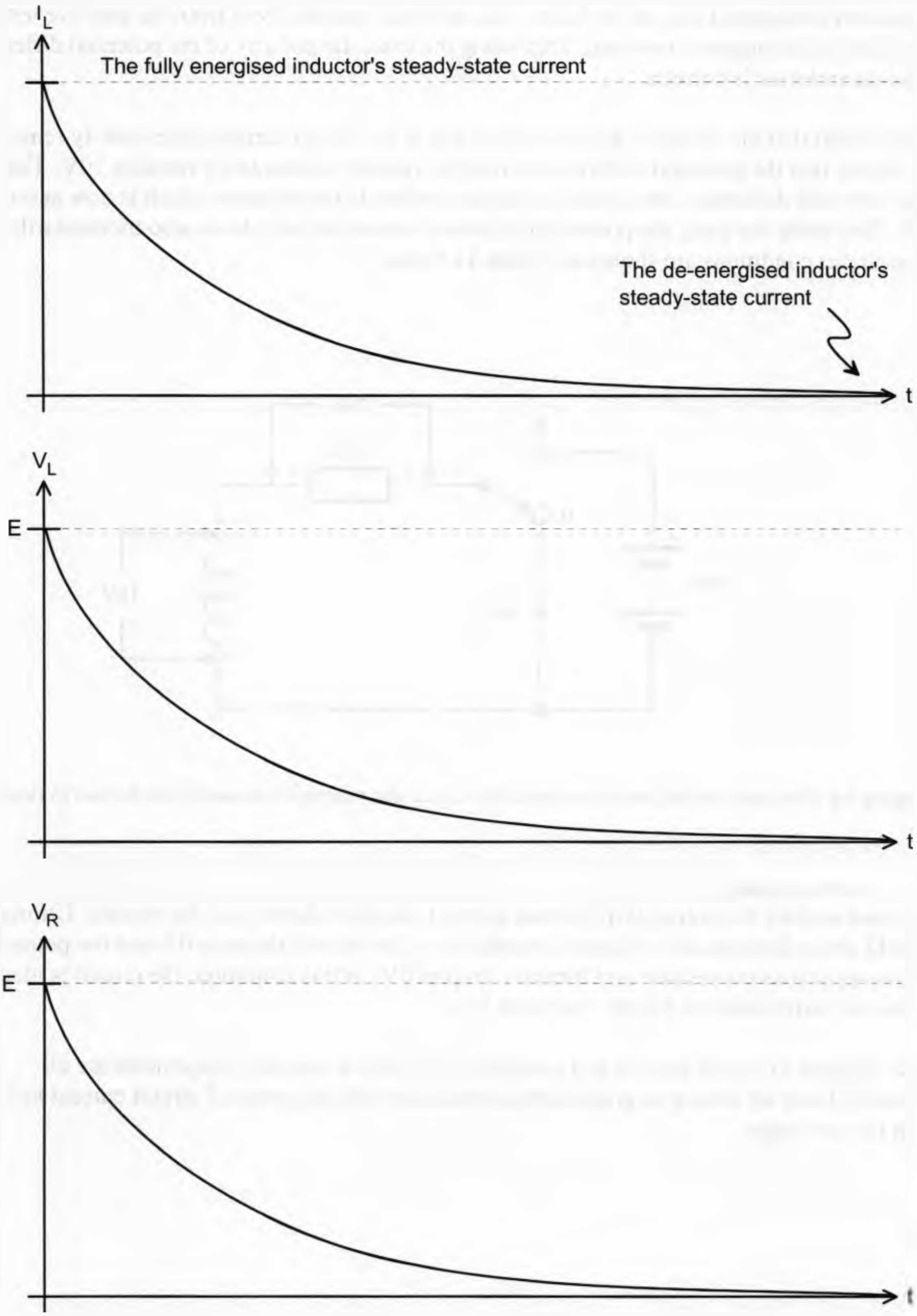


Figure 15 *The graphs of circuit current and potential differences in an RL circuit as the inductor de-energises*

Factors that affect the inductor's energise and de-energise time

There are two factors that affect the time it takes to fully energise and fully de-energise an inductor in an RL circuit. They are: the resistor's value and the inductor's value.

The time it takes to fully energise an inductor is directly proportional to the inductor's value. That is, the higher the inductor's value the longer the charge time. This is because the greater the inductance, the greater the opposition to the circuit current and so the slower the initial rate of change of the circuit current.

The time it takes to fully energise an inductor is inversely proportional to the resistor's value. That is, the higher the resistor's value, the shorter the time it takes for the inductor to fully energise. This is because the bigger the resistor, the smaller the current through the inductor and the smaller the induced current back into the inductor.

Importantly, the EMF's size **doesn't** affect the time taken to fully energise the inductor. Although the changing the EMF's size also changes the size of the current and hence the size of the induced current back into the inductor, it also changes the initial rate of change of current.

For example, doubling EMF doubles the current which doubles the initial rate of change of current and so these two effects cancel each other out. That being the case, if it takes 10 seconds to fully energise a 100mH inductor in a circuit with a 10V EMF, it will take it 10 seconds to fully energise the same inductor in a circuit with a 20V EMF.

Calculating the time it takes to energise and de-energise an inductor

Like the charging of a capacitor, an inductor never fully energises or de-energies. This is because, even though the opposition to changes in current decreases, there is always opposition to even the smallest change needed to finally reach the steady-state current. Hence, it is never reached.

However, like capacitors, it is generally agreed that the inductor is fully energised or de-energised after five time constants when the circuit current is 99.3% of the steady-state current. To calculate this, you must first calculate the time constant of the circuit.

The time constant of an RL circuit can be found by using the equation:

$$\boxed{\tau = \frac{L}{R}}$$

And, the time it takes to fully energise or de-energise an inductor is given as:

$$\boxed{\textit{Energise/de-energise time} = 5 \times \tau}$$

Let's do an example. How long will it take the inductor in Figure 11 below to fully energise or fully de-energise?

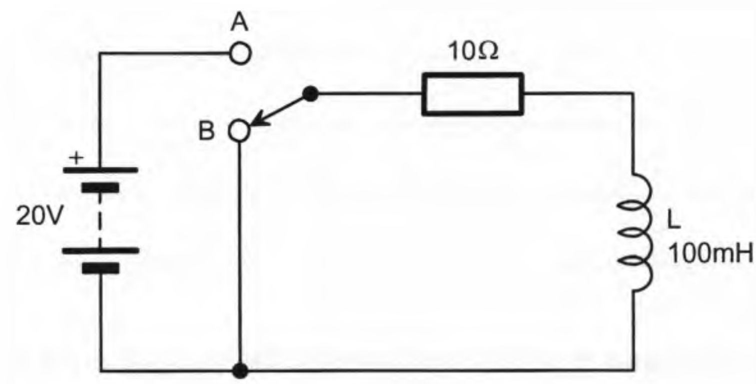


Figure 11

$$\tau = \frac{L}{R}$$

$$\tau = \frac{100mH}{10\Omega}$$

$$\tau = 10ms$$

$$Energise/de\text{-}energise\ time = 5 \times \tau$$

$$Energise/de\text{-}energise\ time = 5 \times 10ms$$

$$Energise/de\text{-}energise\ time = 50ms$$

As mentioned in passing on page 1-13, the maximum curent in the circuit (also known as the *steady state* current) is found just by using Ohms Law. To that end, we assume the inductor is ideal and has no DC resistance. So, in this example, the maximum current is:

$$I = \frac{E}{R}$$

$$I = \frac{20V}{10\Omega}$$

$$I = 2A$$

Practise using these equations for yourself by trying the following questions.

1. How long will it take for a 4.5mH inductor in an RL circuit to fully energise if the series resistor is 330Ω?

2. What value of inductor in an RL circuit would fully energise in 1.8 seconds if the series resistor is 27Ω?

3. What value of resistor in an RL circuit would cause a 300mH inductor to take 100μs to fully energise?

Student notes

Review questions

Answer these questions to check your understanding of what you have learnt for this chapter. Doing this will also help to prepare you for the tests.

Tick the correct box

1. According to Lenz's Law, current in a conductor sets up an electromagnetic field that

- ☐ helps more current to flow.
- ☐ initially opposes the flow of current.
- ☐ doesn't effect the current through the conductor.
- ☐ is relatively short lived.

2. Inductance occurs

- ☐ only in inductors.
- ☐ even when there is no current flowing through a conductor.
- ☐ only at room temperature.
- ☐ whenever the current flowing through a conductor changes.

3. Inductance is measured in

- ☐ Farads.
- ☐ Ohms.
- ☐ Henries.
- ☐ Coulombs.

4. The electromagnetic field about a conductor opposes the flow of current through it

- ☐ only before the current flows.
- ☐ all the time.
- ☐ only as the field expands or contracts.
- ☐ when the field is at maximum.

5. An inductor is a component that

- ☐ develops an electromagnetic field.
- ☐ has a resistance that approaches infinity.
- ☐ stores electrical charge.
- ☐ is made from semiconductor materials.

6. What can the core of an inductor be made from?

- ☐ Ferrite
- ☐ Soft iron
- ☐ Air
- ☐ All of the above

7. Reducing the number of turns in an inductor

- ☐ increases its inductance.
- ☐ doesn't have an affect on its inductance.
- ☐ decreases its inductance.
- ☐ has a small but insignificant affect on its inductance.

8. Reducing the length of an inductor, without reducing the number of turns

- ☐ increases its inductance.
- ☐ doesn't have an affect on its inductance.
- ☐ decreases its inductance.
- ☐ has a small but insignificant affect on its inductance.

9. Using aluminium wire instead of copper wire to make an inductor

- ☐ increases its inductance.
- ☐ doesn't have an affect on its inductance.
- ☐ decreases its inductance.
- ☐ has a small but insignificant affect on its inductance.

10. Increasing the permeability of the core of an inductor

- ☐ increases its inductance.
- ☐ doesn't have an affect on its inductance.
- ☐ decreases its inductance.
- ☐ has a small but insignificant affect on its inductance.

11. Increasing the thickness of the wire in an inductor

- ☐ increases its inductance.
- ☐ doesn't have an affect on its inductance.
- ☐ decreases its inductance.
- ☐ has a small but insignificant affect on its inductance.

12. What type of inductor is shown in Figure 1?

- ☐ Fixed value air core inductor
- ☐ Variable air core inductor
- ☐ Fixed value soft iron core inductor
- ☐ Variable soft iron core inductor

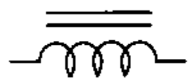


Figure 1

13. Which of the following inductors are polarised?

- ☐ Ferrite
- ☐ Soft iron
- ☐ Air
- ☐ None of the above

14. Draw the schematic symbol for a variable ferrite core inductor.

15. List the four factors that affect the inductance of an inductor.

16. Give two applications for inductors in electrical circuits.

17. How would you test an inductor to check that it is functional without using an LCR meter?

18. What is the *time constant* of an RL circuit?

19. What is the relationship between circuit resistance and time constant in RL circuits?

more questions on the next page . . .

Questions 20 to 25 refer to the circuit in Figure 2

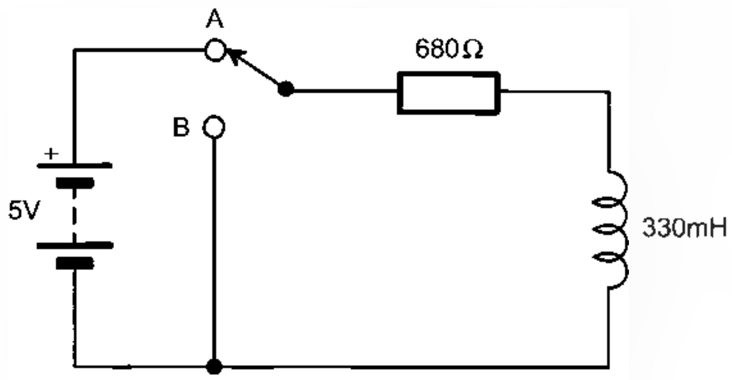


Figure 2

20. Calculate the circuit's time constant (τ)?

---

21. How long will it take the current in the circuit to reach maximum?

---

22. What is the maximum current that will flow (assume that the inductor is ideal)?

---

23. How long will it take the circuit current to drop to zero when SW1 is switched to the position B?

24. What will happen to the time it takes for the current to reach maximum if the EMF is halved?

- ☐ It would double
- ☐ It would decrease by four times
- ☐ It would halve
- ☐ It would remain the same

Questions 25 and 26 refer to the circuit of Figure 3

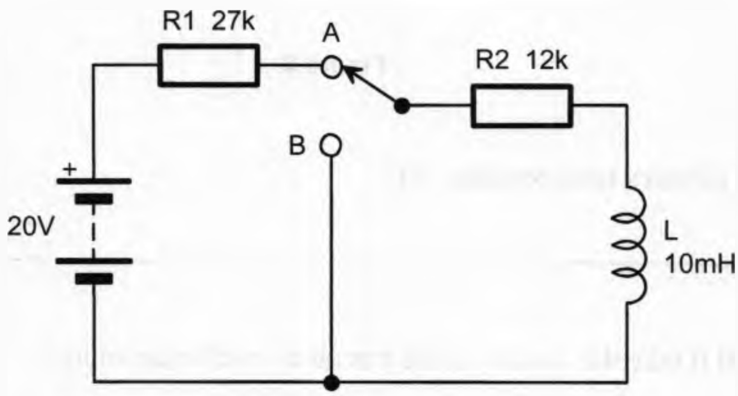


Figure 3

25. How long will it take for the circuit current to reach maximum?

____

____

26. How long will it take for the circuit current to drop to zero when SW1 is switched to the position B?

____

____

Section 2 Alternating voltages and currents

Purpose To develop your ability to identify and compare alternating voltages and currents in electrical and electronic circuits.

Objectives At the end of this section you should be able to:

- Explain the difference between alternating current (AC) and direct current (DC)
- Recognise AC waveforms including symmetrical and non-symmetrical sinewaves, squarewaves and triangular waves
- Explain the advantage of using AC voltages for power distribution over DC voltages
- Explain how a sinewave is generated
- Define the following terms with regard to sinewaves: *period*, *frequency*, *peak*, *peak-to-peak*, *instantaneous* and *RMS*
- Calculate either the peak, peak-to-peak, instantaneous or RMS value of a sinewave voltage/current given one of the other values
- State the unit of measurement for *frequency*
- Calculate either the frequency or period of a sinewave given the other
- List the properties of AC signals that can be measured using typical multimeters
- List the advantages and disadvantages of measuring AC signals with typical multimeters
- Use a digital multimeter to measure AC voltage and current in a simple circuit

Introduction

In your studies so far you've learnt about several important components used in electronics: the resistor, the capacitor and the inductor. You've also learnt about what these components do and how they perform in DC circuits.

DC is an important type of voltage in electronics but AC is just as important and it is used extensively (not just for power to houses). That being the case, this subject introduces you to the properties of AC voltages and currents and how resistors, capacitors and inductors perform in AC circuits. There are many similarities in this regard to DC circuits but there are also some important differences.

Direct current

Figure 1 below shows a DC source connected to three resistors in series. This is a DC circuit and you'll probably remember that (conventional) current flows in the direction shown. Importantly, as long as the EMF is connected in the polarity shown the direction of current through the resistors wont change. Furthermore, if the EMF is "ideal" its voltage is constant and so the current in the circuit is constant also.

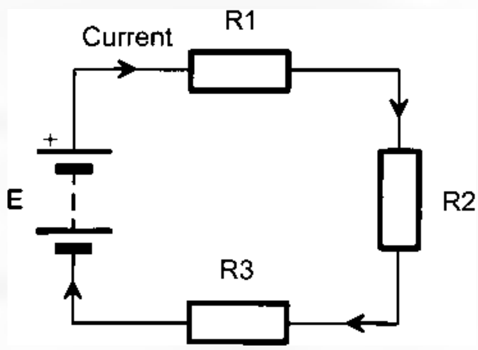


Figure 1 *Current flows in the one direction in a DC circuit*

Figure 2 below shows the graphs of EMF voltage and circuit current versus time.

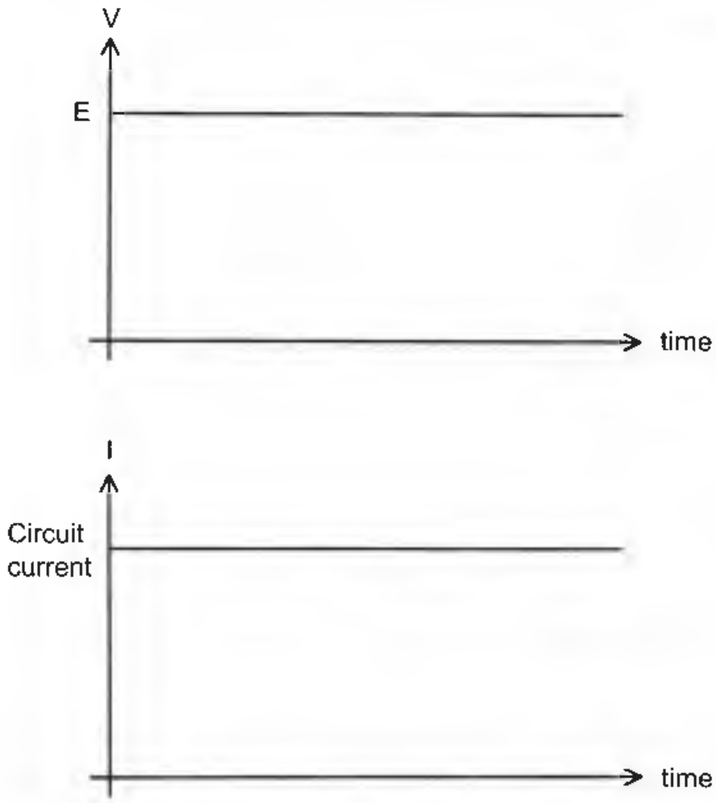


Figure 2 *The graphs of EMF versus time and circuit current versus time for a DC circuit*

Alternating current

AC is different to DC because the size of AC voltages and currents change over time, reversing direction at fixed intervals. This is illustrated in Figure 3 below using the example of an AC voltage called a *sinewave*.

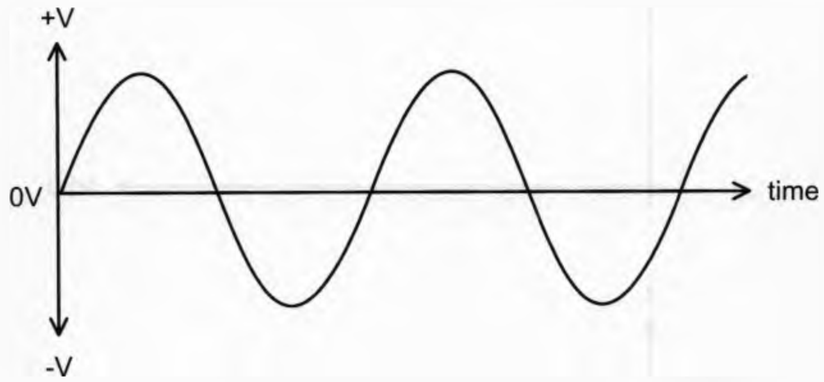


Figure 3 *The example of the sinewave above illustrates the regular polarity reversal of AC*

Starting from the beginning of the graph (the left end), the sinewave's voltage starts at zero and steadily increases to maximum in the positive direction. Once it reaches maximum, it changes direction and steadily decreases back to 0V then on to a second maximum in the negative direction.

If this sinewave is substituted for the DC source in Figure 1, the circuit current looks Figure 4 below.

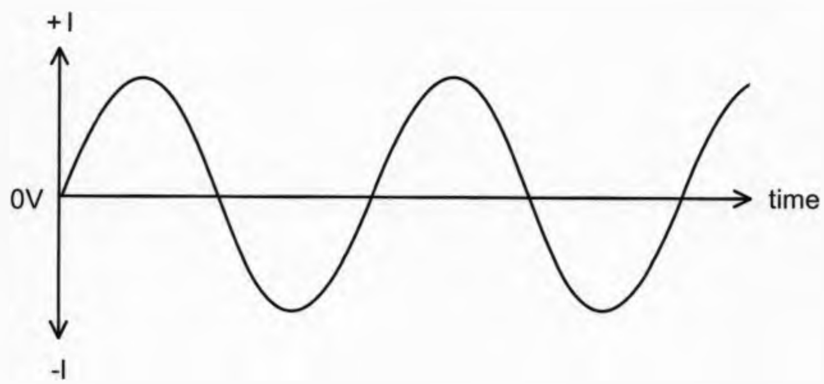


Figure 4 *The current in a series resistive circuit with a sinewave AC voltage as the source*

The sinewave isn't the only type of AC signal. Other AC signals are shown in Figure 5 below.

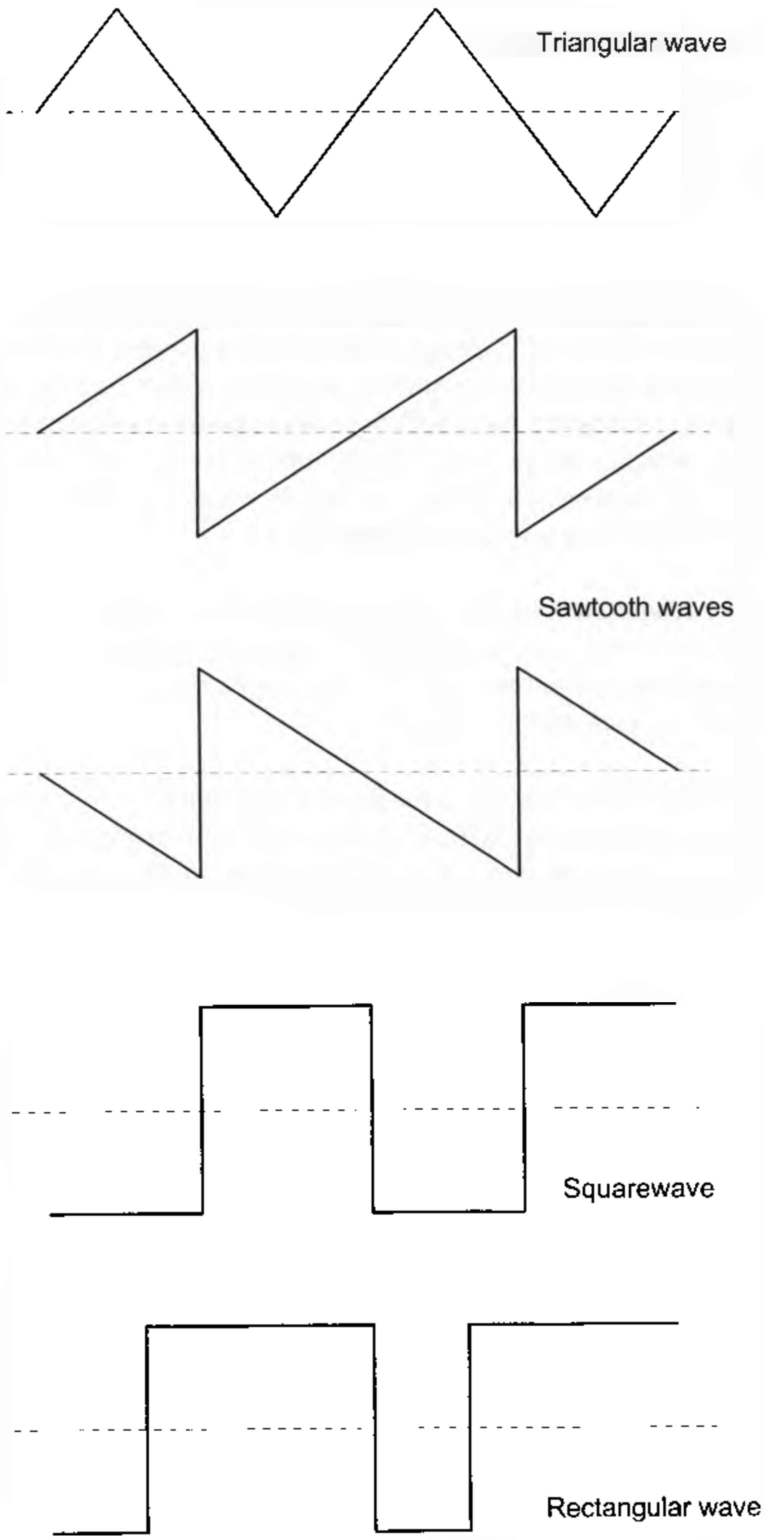


Figure 5 *There are many types of AC signals*

There are other types of non-symmetrical AC waveforms but you'll learn about them in later subjects.

Why do I need to know about AC?

These days, AC is used almost universally for the distribution of electricity from power stations to towns and cities. This wasn't always the case. The first electricity distribution systems were DC (even here in Sydney!). However, DC distribution is considerably inefficient because of the substantial cable losses that occur at useable voltages.

AC lends itself to being converted from low voltages to high voltages and back again very easily (using transformers which you'll learn about later). In the process, the current always changes in the opposite way. That is, if an AC voltage is made bigger using a transformer, the current is made smaller. That being the case, transmitting AC along power lines at much very high voltages (eg 33kV and 330kV) reduces the current flowing through the cables and makes the cable-losses negligible. The high voltages are converted back into relatively low voltages (eg 240V and 415V) at the street level using another transformer for supply to domestic and commercial buildings. [Mathematical proof of this is provided in Appendix 1.]

This is important for technicians to know about because most electronics equipment (such as televisions, stereos, computers and so on) need DC power to operate not AC. That being the case, most electronics equipment contains a unit called a *power supply* that converts the 240V AC into DC voltages for use by electronics equipment.

While it's the job of electricians to wire suburbs and buildings for AC, it's usually the job of technicians to repair the power supply in equipment that converts the AC to DC. Moreover, power supply faults are common in electronics equipment so it'll not be long before you have to repair one. Power supplies are discussed in detail in two other subjects and a good understanding of AC principles is a prerequisite.

There's another important reason for technicians to know about AC. All "intelligence" that is communicated electrically (eg radio, television and mobile phone signals) is done so as AC. Consider the simple act of talking into a microphone for example. The microphone converts your voice into a voltage that, when you think about it, must be AC because as you talk the tone, pitch and volume of your voice go up and down. This means that the voltage produced must be changing and size and reversing direction.

Even digital systems such as computers use AC signals. To explain, digital electronic circuits work with *bits* called "1s" and "0s" that are represented by two different voltages (eg 5V for a 1 and 0V for a 0). Importantly, the bits change back and forth between 1 and 0 at very high speeds producing signals that look similar to the rectangular wave on the previous page.

The fact is, it doesn't matter what you repair as a technician, you can't avoid AC and so you need to know a fair bit about it.

Generating AC

A simple AC generator is shown in Figure 6 below.

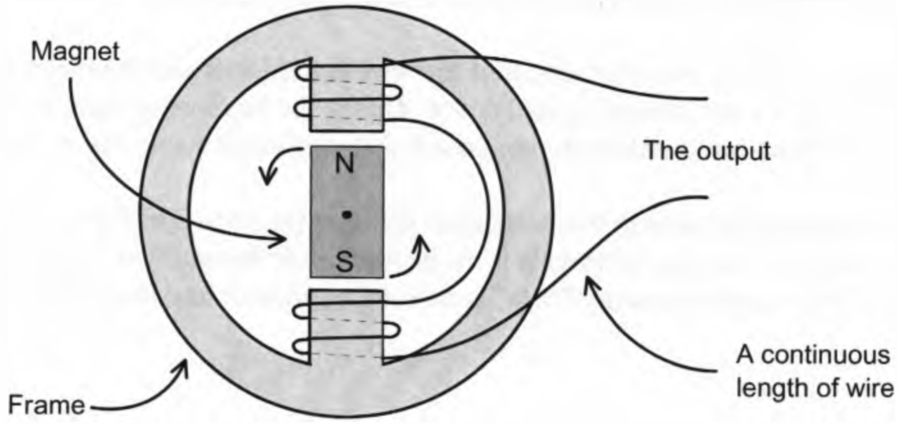


Figure 6 *A simple AC generator*

The operation of a generator relies on the effect that occurs when a wire is moved inside an electromagnetic field (see Figure 7 below).

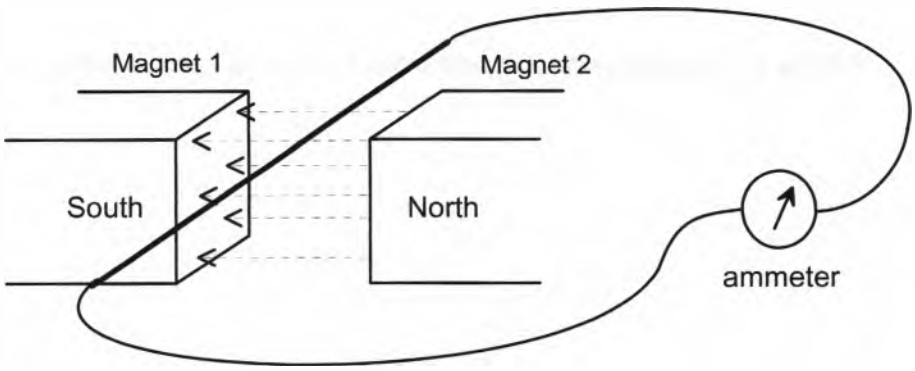


Figure 7 *Current flows in a conductor when it is moved perpendicular within a magnetic field*

When the wire is moved either up or down (that is, perpendicular to the magnetic field) an electrical current is induced in the wire. Furthermore, if the wire is made to move up and down continuously then the current that is produced is AC. To explain, as the wire moves in an upward direction, a current is developed in the wire in one direction. As the wire changes direction, it stops momentarily and so the current drops to zero but then increases to maximum again in the opposite direction as the wire moves in a downward direction.

The same effect as this is produced if the wire is held still and the magnets - and hence the magnetic field - are moved up and down. This is the basis of operation of the simple generator in Figure 6 which has a stationary conductor that surrounds a rotating magnet.

When the magnet starts in the horizontal position (as shown in Figure 8 below) the magnetic energy around the magnet travels from its north pole to south pole through the air. As a result, none of the magnetic energy "cuts" across the conductor and the output voltage is zero.

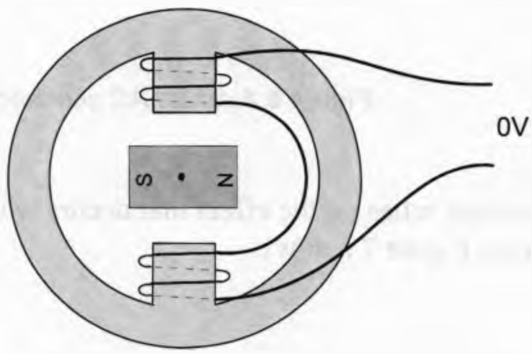


Figure 8 *The output voltage is zero when the magnet is in the horizontal position*

When the magnet rotates (anti-clockwise in this example) an increasing amount of its magnetic field prefers to travel from the magnet's north pole to south pole via the frame because it is made from a material (such as soft-iron) which is a better conductor of magnetic energy than air. As the conductor is wired on the arms of the frame, the magnetic energy flowing through the frame starts to cut across the conductor and an output voltage is developed.

The output voltage continues to increase until the magnet's position reaches a quarter of a rotation (see Figure 9a). At this point nearly all of the magnet's magnetic field is travels through the frame and the output voltage is maximum. But, as the magnet continues to rotate, the magnetic energy in the frame decreases reaching zero again when it is back in the horizontal position (see Figure 9b). At this point the output voltage is minimum.

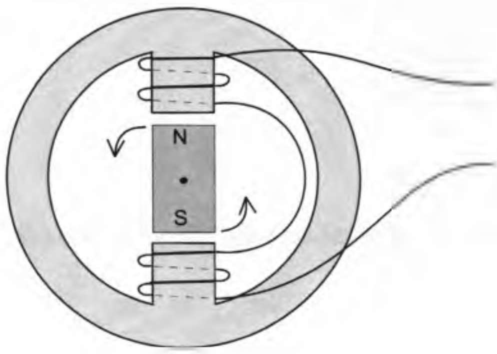


Figure 9a *The magnetic energy in the frame is maximum so the output voltage is maximum*

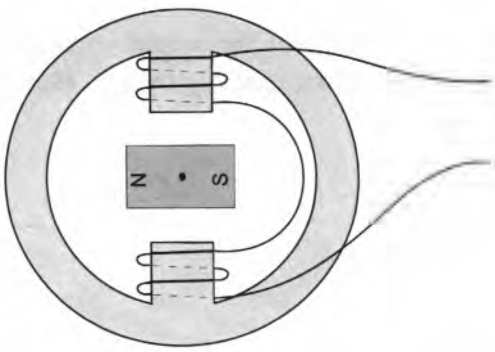


Figure 9b *The magnetic energy in the frame is zero so the output voltage is zero*

As the magnet continues its rotation, the magnetic energy in the frame increases again reaching another maximum when the magnet is three quarters of the way around a revolution (see Figure 10). This means that the output voltage will be at maximum again too. However, because the magnet's south pole is where its north pole was and vice versa, the polarity of the output voltage is opposite to the polarity to the output voltage when the magnet had rotated only a quarter of a revolution.

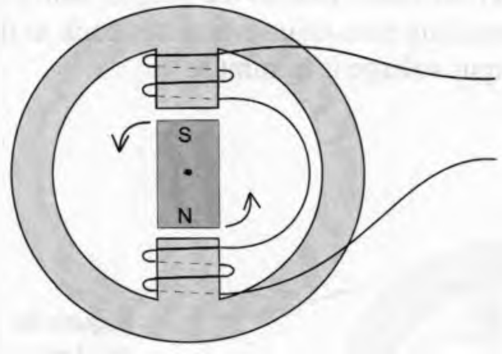


Figure 10 *When the magnet has travelled three quarters of a revolution the output voltage is maximum again but in the opposite polarity*

During the last quarter of the revolution, the magnetic energy in the frame decreases again reaching zero when it is in the original starting position. Consequently, the output voltage returns to zero also.

At this stage, you might be tempted to think that the waveform of the output voltage should look like two semi-circles connected together with one upside-down (see Figure 11). But, this is not quite the case!

Figure 11 *Despite what you might guess, the generator's output voltage doesn't look like this*

The reason the AC waveform doesn't look like the drawing in Figure 11 can be understood if the magnet's movement is considered from the position of the windings. Although the magnet's rotation speed is constant, as the ends of the magnet approach the windings, the angle of travel changes and so the apparent speed appears to slow down then reverse direction.

As a result, the generator's output looks like a sinewave (as shown in Figure 12) instead of inverted semi-circles connected at their ends (as shown in Figure 11).

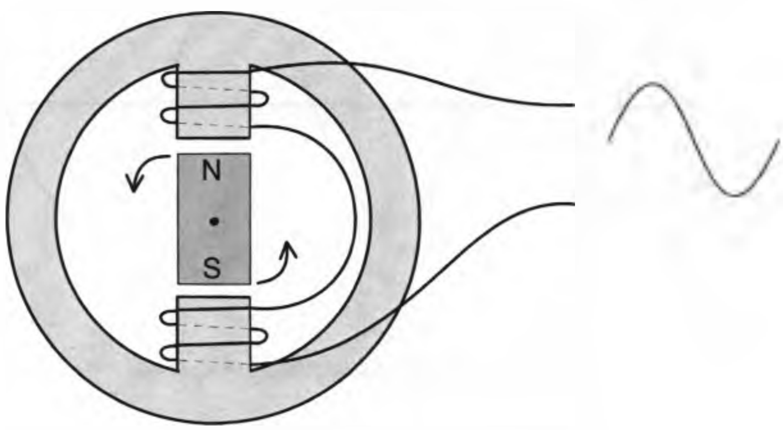


Figure 12 *The output of an AC generator is a sinewave*

Although there are many different types of AC waveforms, the sinewave is used most throughout this workbook when discussing AC. There are a few reasons for this. First, as just discussed, AC generators make sinewaves and so mains voltages are sinewaves. Second, when learning about the properties of AC it is easier to learn about them using the sinewave. Third, the sinewave makes an excellent "test signal" when testing electronics equipment (such as amplifiers) so you'll use it often in your work as a technician.

The cyclical nature of sinewaves

Any pattern that repeats itself is said to be a "cycle". If you travel along a sinewave starting at any point, eventually you'll arrive at a point where the sinewave starts to repeat itself (see Figure 13). This is true regardless of where in the sinewave you start. That being the case, sinewaves are cyclical also.

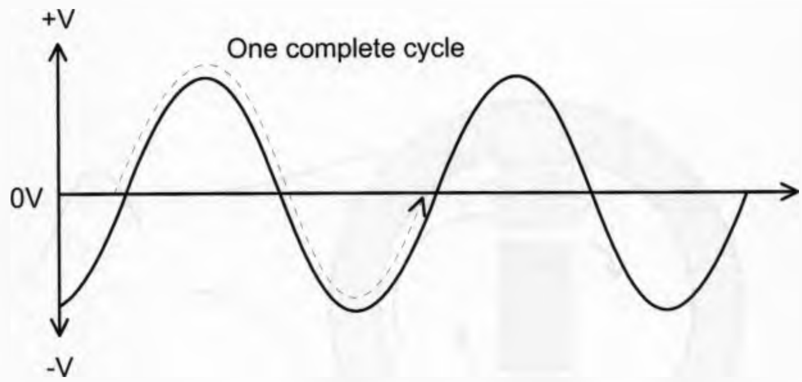


Figure 13 *Sinewaves are cyclical*

One full cycle of a sinewave is equivalent to one revolution of the generator's magnet. And, as any instant in the rotation of a spinning object can be described in degrees, then any instant in one cycle of a sinewave can also be described as an angle in degrees. This is shown Figure 14 below.

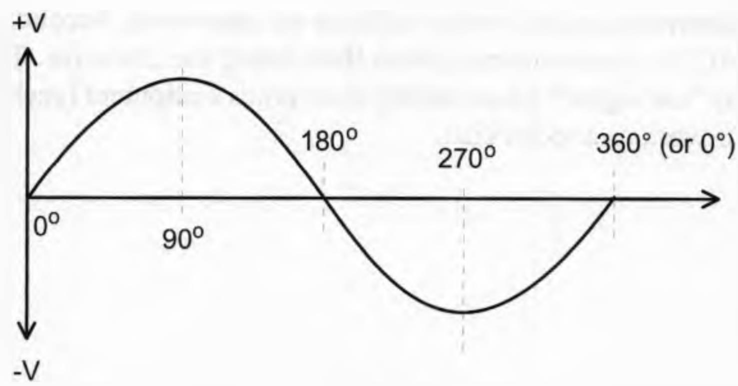


Figure 14 *The angles of one complete sinewave*

Notice that the 360° point (or the end) of one cycle doubles as the 0° degree point (or the start) of the next cycle.

Sinewave properties

There are several important properties of AC waveforms that technicians regularly compare. These are:

- Peak-to-peak voltage (or current)
- Peak voltage (or current)
- Instantaneous voltage (or current)
- RMS voltage (or current)
- Period
- Frequency

The following notes explain each of these.

Peak-to-peak voltage

The term *peak* is used to name the points of an AC waveform that are the highest in either direction. That being the case, the *peak-to-peak* voltage is the size of the AC waveform from the lower (or negative) peak to the upper (or positive) peak and is measured in volts. This is shown in Figure 15 below.

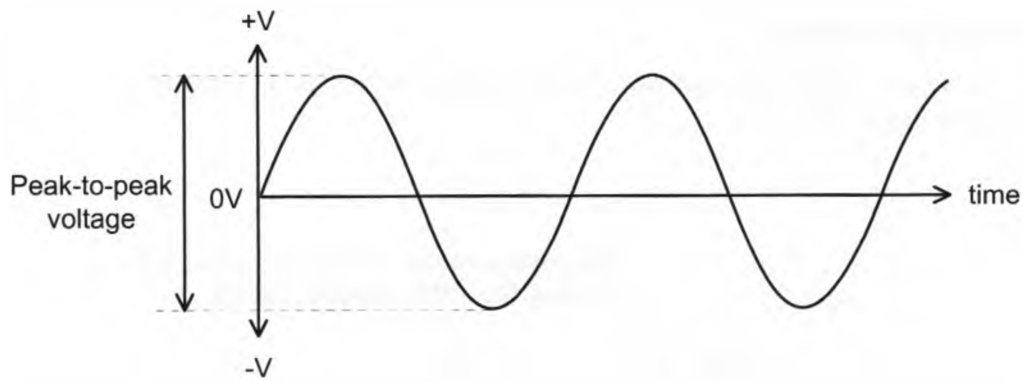


Figure 15 *The peak-to-peak voltage of an AC waveform*

Technicians measure the peak-to-peak value of AC signals when checking signals to locate the problem in faulty equipment such as amplifiers. The peak-to-peak voltage is usually measured using an oscilloscope which you'll learn more about in the next section.

Peak voltage

The *peak* voltage is the size of the AC waveform from the zero line to either the negative peak or the positive peak and is measured in volts. This is shown in Figure 16 below.

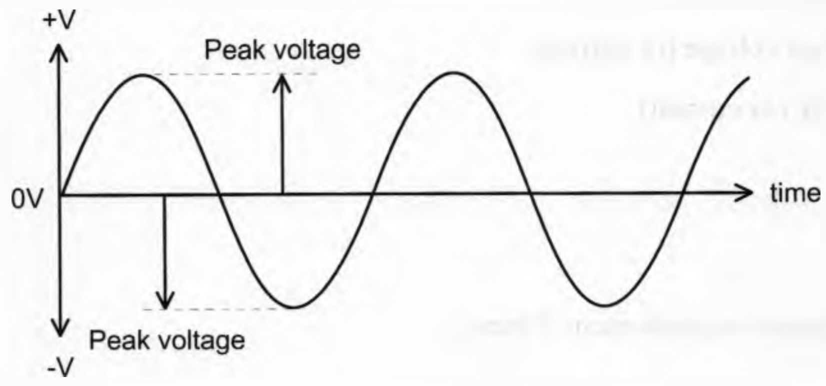


Figure 16 *The peak voltage of an AC waveform*

The positive and negative peak voltages are always the same as each other for true sinewaves. Technicians measure the peak value of AC signals when testing power supplies and it can be measured using an oscilloscope.

Instantaneous voltage

The *instantaneous* voltage of a sinewave is the voltage at any point (that is, at any instant) in the sinewave (see Figure 17).

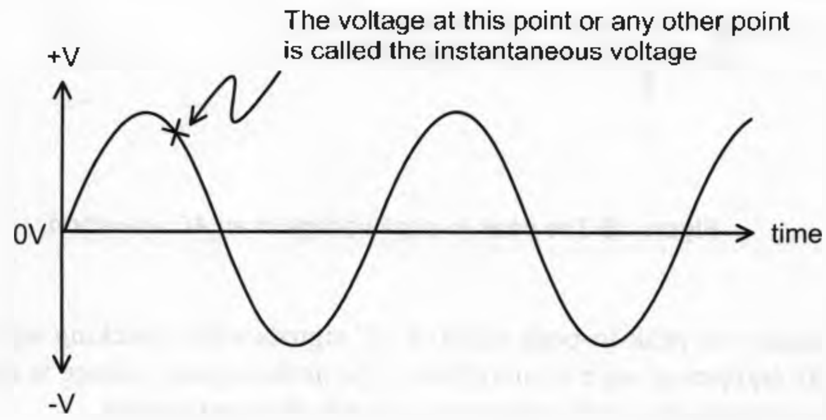


Figure 17 *The voltage at any instant of a waveform is called the instantaneous voltage*

The instantaneous voltage can be calculated if the exact angle of the instant is known as well as the waveform's peak voltage using the equation:

$$v = V_{(pk)} \times Sin\theta$$

The equation explains why a sinewave is so called. To demonstrate how to use it, let's find the instantaneous voltage at 50° of the sinewave in Figure 18.

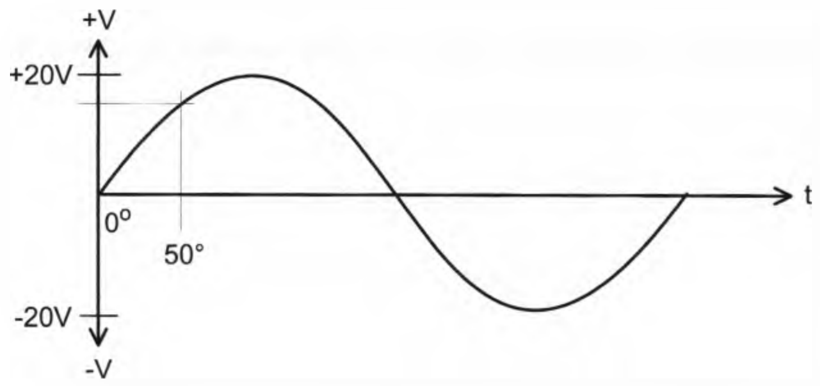


Figure 18

A simple visual inspection should tell you that the instantaneous voltage is about three quarters of the peak voltage. Putting the relevant values into the equation and solving gives:

$$v = V(pk) \times Sin\theta$$

$$v = 20V \times Sin50^{o}$$

$$v = 20V \times 0.766$$

$$v = 15.32V$$

Practise calculating the instantaneous voltage of a sinewave for yourself by trying the following questions.

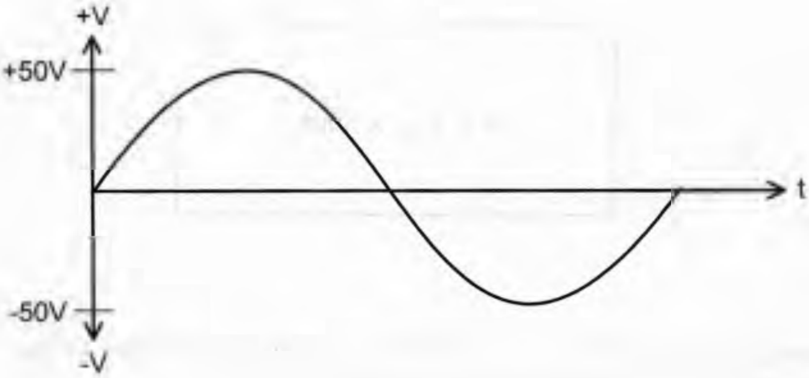


Figure 19

1. Indicate on the sinewave in Figure 19 above the approximate position of the following angles:

   a) 45°
   b) 90°
   c) 200°
   d) 300°

2. Calculate the instantaneous voltage of the sinewave at the same angles:

   45° = 35.36 V

   90° = 50 V

   200° = − 17.10 V

   300° = − 43.30 V

In terms of the day-to-day work of a technician, you're unlikely to measure the instantaneous value of a voltage or current sinewave. However, it is important that you know how to calculate it because the idea underpins other important concepts that you'll learn about later in the course.

RMS voltage

Recall from earlier work that if the potential difference across a component (or circuit) and the current through it are known we can calculate the power that it dissipates (using the equation $P = I \times V$).

However, we can't use either the peak or instantaneous values of voltage and current to calculate AC power because this will only give us the power being dissipated at that point (or instant) in the waveform. The calculation wouldn't tell you how much power is being dissipated over time which is far more important because that's the power you're paying for and it determines how hot the component gets.

To calculate the power dissipated in AC circuits over time, it would be tempting to use the average values of voltage and current. However this is problematic for two reasons. First, the average value of a pure sinewave voltage/current is always zero. To prove this, consider the sinewave in Figure 20 below.

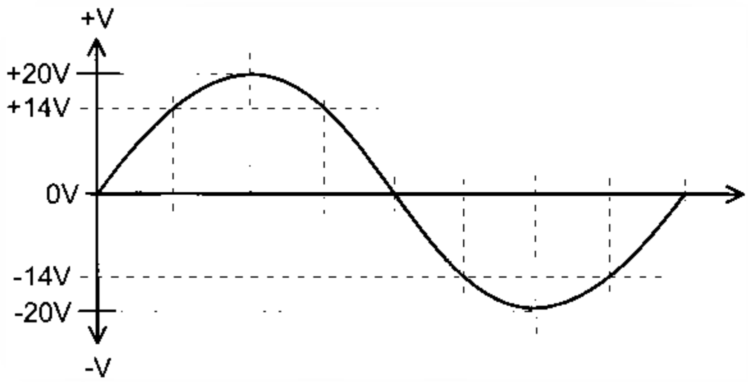


Figure 20 *A sinewave with known voltages at eight equidistant points*

The voltage at eight equidistant points is known and they are +14.1V, +20V, +14.1V, 0V, -14.1V, -20V, -14.1V and 0V. To calculate the average, simply add the numbers up and divide by eight. If you do the maths you'll find the answer is zero.

The second problem is that, because of the *square law* effect of power (that is, an increase in voltage produces an increase in power equal to the square of the increase of the voltage or $P = \frac{V^2}{R}$), all of the voltages across a sinewave are not equal in effect. For example, the power at the instant that the sinewave is 20V is much greater than double the power at the instant that the sinewave is 10V.

To overcome these problems and arrive at a figure that can be used with power calculations, a mathematical process called *Root Mean Square* (*RMS*) is used. Let's apply the process on the samples on the previous page. Their squared values are 198.8V, 400V, 198.8V, 0V, 198.8V, 400V, 198.8V and 0V. Then, they are then added together and divided by eight to obtain the average (which gives 200). This number is then square-rooted to return the answer to the correct proportion. If you try this, you'll find that the RMS of the waveform in Figure 20 is 14.14V.

Importantly, the *RMS* value of an AC waveform has the same heating effect as a DC voltage of the same value. In other words, the heating effect of the 40Vp-p sinewave in Figure 20 is equivalent to 14.14V DC.

The more convenient way to calculate the RMS value of sinewave voltages or currents is to use the equations below:

$$\boxed{V_{RMS} = V_{(Pk)} \times 0.707} \quad \text{and} \quad \boxed{I_{RMS} = I_{(Pk)} \times 0.707}$$

To check the equation let's use it on the sinewave in Figure 20.

$$V_{RMS} = V_{(Pk)} \times 0.707$$

$$V_{RMS} = 20V_{Pk} \times 0.707$$

$$V_{RMS} = 14.14V$$

Practise calculating the RMS value of a sinewave using peak and peak-to-peak values for yourself by trying the following questions.

1. What is the RMS current of a 320mA (peak) current?

   226.3mA RMS

2. What is the RMS voltage of a 180V (peak-to-peak) sinewave?

   63.6V RMS

If you know the RMS value and instead want to calculate the peak value then the equation $V_{RMS} = V_{(Pk)} \times 0.707$ is transposed to make V_{Peak} the subject.

$$V_{RMS} = V_{(Pk)} \times 0.707$$

$$\frac{V_{RMS}}{0.707} = V_{(Pk)}$$

$$V_{(Pk)} = V_{RMS} \times \frac{1}{0.707}$$

$$V_{(Pk)} = V_{RMS} \times 1.414$$

Practise calculating the peak and peak-to-peak values of sinewaves from RMS values for yourself by trying the following questions.

1. What is the peak voltage of a 22V sinewave?

   1, 414 V PEAK

2. What is the peak-to-peak current of a 120mA current?

   31. 11 V PEAK

Technicians measure the RMS value of AC signals when dealing with mains voltages or to calculate the power in AC circuits. The RMS voltage or current is measured with a voltmeter or ammeter (such as on a DMM) but it cannot be measured with an oscilloscope.

Period

The period of an AC waveform is the time it takes to complete one full cycle and is measured in seconds. An example of a sinewave that takes 100ms to complete a cycle is shown in Figure 21 below.

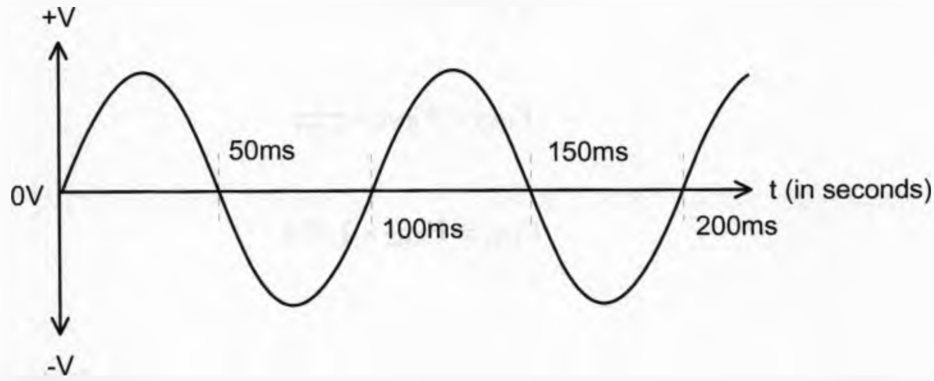


Figure 21 *A sinewave with a period of 100ms*

Frequency

The term "frequency" simply means *how often a cyclical event occurs*. In our everyday world, we measure the frequency of all sorts of things: for example, a person's heart rate (in beats per minute) or an engine's rotation (in revolutions per minute or just rpm).

Not surprisingly, in electronics we're interested in the frequency of AC signals. That is, we like to specify how many cycles of the AC signal occur in a given amount of time. However, we use the second for our time reference and not the minute because the second is the *standard* unit of measurement for time.

So the *frequency* of an AC signal is simply the *number of cycles per second*. The unit of measurement for frequency is the *Hertz* (Hz). For example, a signal that produces 500 cycles per second is said to have a frequency of 500Hz.

The frequency of an AC signal can be determined if its period is known. Consider the sinewave in Figure 22. Each cycle has a period of a quarter of a second. Logically then, four complete cycles occur in one second and this is shown in the diagram. That being the case, the signal has a frequency of 4Hz.

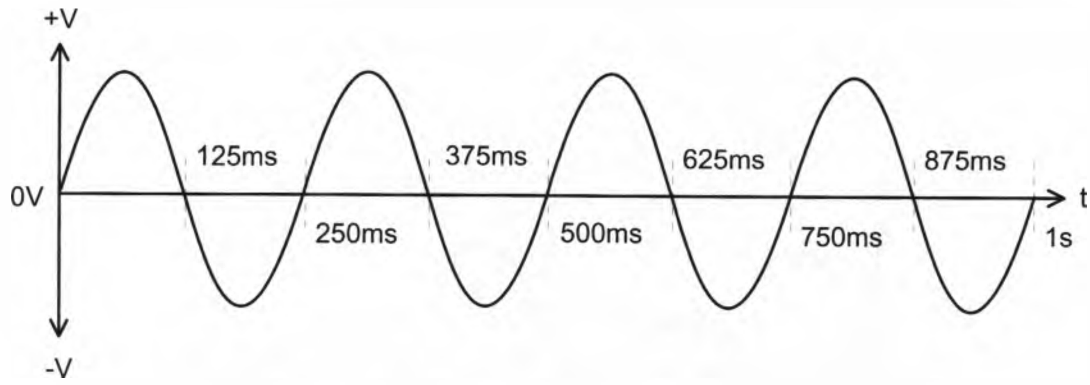


Figure 22 *A sinewave with a period of 250ms*

Calculating the frequency of a signal from the period using common sense like this is a little more tricky when the numbers get smaller. For example, what is the frequency of a signal with a period of 25µs?

Actually, it's not that tricky when you think about it. If one cycle occurs in 25µs and what you want to know is how many cycles occur in one second then, what you really want to know is how many lots of 25µs occur in 1s. Mathematically all that need be done is divide 1s by 25µs to get the answer. If you try it you'll find the answer is 40,000. So, the frequency of a signal with a period of 25µs is 40kHz.

This gives us a general equation that can be used to calculate the frequency of an AC signal from its period.

$$\boxed{f = \frac{1s}{P}}$$

Where:
f is frequency and
P is the period of the waveform

Practise calculating the frequency of sinewaves for yourself by trying the following questions:

1. What is the frequency of the AC signal in Figure 23?

500 HZ

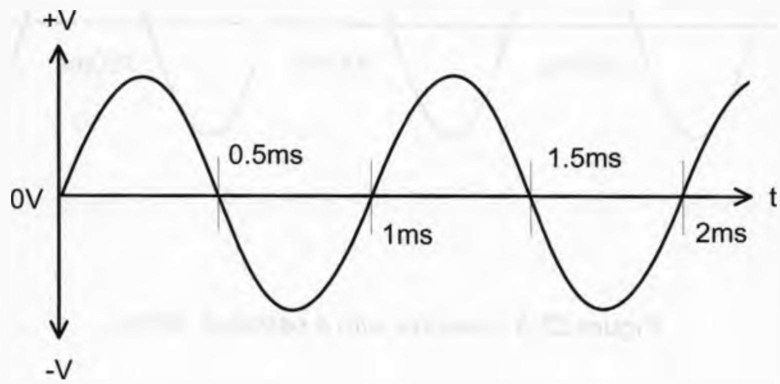


Figure 23

2. What is the frequency of an AC signal with a period of 820ns?

1.22 MHz

If you know the frequency of the waveform and instead want to calculate the period then the equation $f = \frac{1s}{P}$ is transposed to make P the subject.

$$f = \frac{1s}{P}$$

$$f \times P = 1$$

$$P = \frac{1s}{f}$$

Practise calculating the period of a sinewaves from frequency for yourself by trying the following questions:

1. What is the period of a sinewave with a frequency of 5kHz?

200 microseconds

2. What is the period of a sinewave with a frequency of 2.25MHz?

444 nanoseconds

Student notes

Skill practice 2

Practise measuring AC voltage and current using a digital multimeter

This exercise is practise for the sorts of skills you may be required to perform in a practical test. Remember, in any practical tests you will be working alone so make sure that you can perform all the steps. It should take you about 1 hour to complete this exercise.

Equipment

- dual output AC power supply
- interface panel
- digital multimeter
- 1kΩ ¼W resistor
- banana leads

Remember:

Follow TAFE NSW WHS guidance at all times!

Work tasks

1. Read your WHS responsibilities at the top of the form below. Then conduct a WHS risk assessment and record your findings in the space provided.

Responsibilities of students under the Model WHS Act: s28

- Take reasonable care for your own health and safety by working safely at all times
- Take reasonable care to ensure that your acts or omissions don't put the health and safety of others at risk
- Follow all TAFE NSW WHS guidance and comply with all reasonable instructions from TAFE NSW staff to assist them in complying with the TAFE NSW WHS requirements
- In addition to the above, you must:
  - use and maintain machinery, tools and all other equipment properly and safely
  - ensure that your work area is free of hazards
  - notify a TAFE NSW staff member of actual or potential hazards
  - wear/use prescribed safety equipment
  - take notice of any safety signs and adhere to their instructions

Risks involved in this activity include:	**Control measures:**
Trip hazards (eg students bags) Objects dropped on feet (while equipment is taken to and from workbenches). Others: Bags and Stuff	Move bags and other objects from walkways Plan lifting of equipment Other: Bags moved Spece cleared

My signature here indicates that I have read and understand my responsibilities under the Model WHS Act s28 (detailed above). I have also conducted a risk assessment before undertaking this activity and have identified measures to control these risks and have implemented them.

Signature: ________ Date: 08/04/25

2. Gather the equipment needed for this exercise.

3. Set up the DMM for measuring AC voltages.

   Note: Use the "V" setting with the little sinewave drawn above it.

4. Plug in the dual AC power supply and turn it on at the mains outlet (the GPO).

5. Measure the voltage of one of the AC power supply's outputs (between one pair of blue and yellow terminals). Record this voltage below.

   The AC power supply voltage is: 17.9 V

6. Remeasure the voltage of the AC power supply's output but this time reverse the connection of the meter's probes to the supply's output terminals. Note whether the polarity and/or the size of the voltage changed.

Question 1
Why did the DMM's voltmeter measure the same polarity no matter which way around the probes were connected to the supply's output terminals?

Polarity did not change

Question 2
What type of AC voltage did the meter give you?

- ☐ Peak-to-peak
- ☐ Peak
- ☑ RMS
- ☐ Average

Question 3
Convert the measured voltage to peak voltage.

$V_{PEAK} = V_{RMS} \times \sqrt{2} = 25.3V$

Question 4

Convert measured voltage to peak-to-peak voltage.

50.62v

Question 5

What type of waveform is the AC power supply's output?

- [x] Sinewave
- [ ] Squarewave
- [ ] Triangular wave
- [ ] Irregular wave

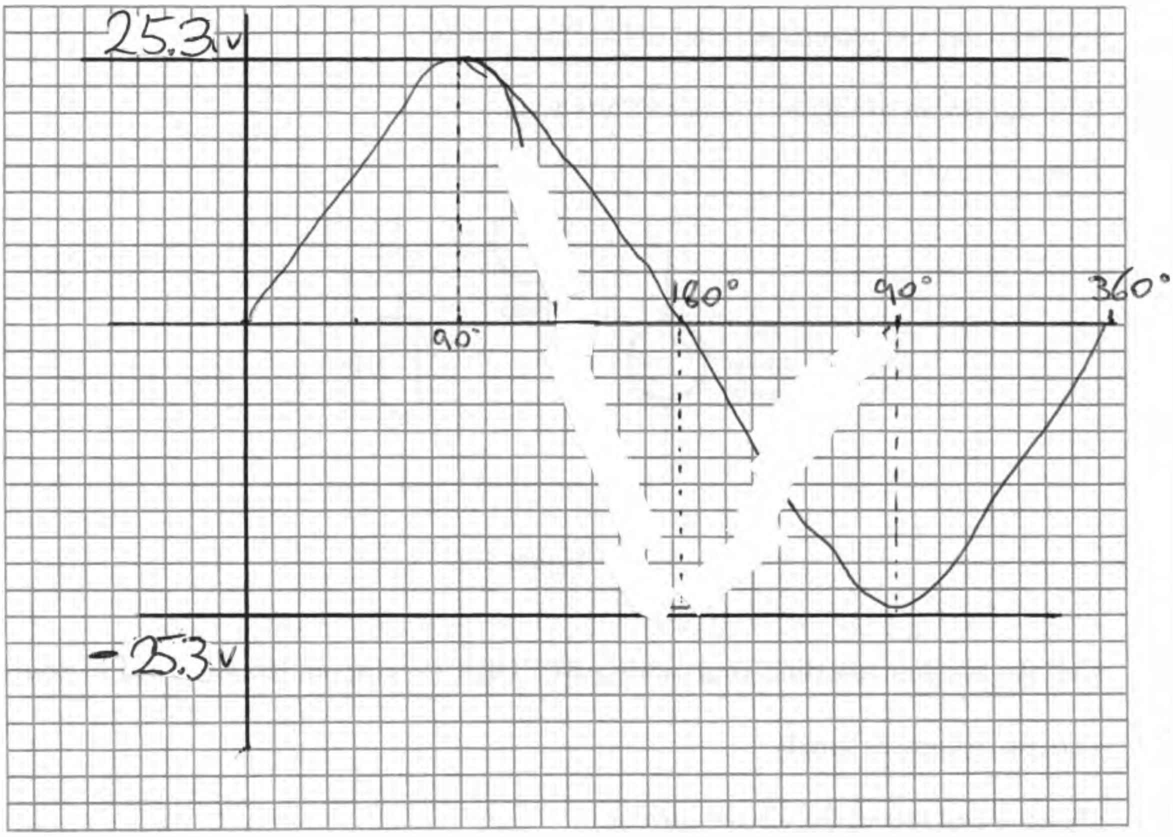
Question 6

Calculate the waveform's instantaneous voltage at the angles listed below using the peak voltage (calculated for question 3) and the equation: $v = V(pk) \times Sin\theta$.

30°	= 12.66v	210°	−12.66v
60°	= 21.93v	240°	−21.93v
90°	= 25.31v	270°	−25.31v
120°	21.93v	300°	−21.93v
150°	12.66v	330°	−12.66v
180°	0v	360°	0v

The teacher needs to check your work at this point...

7. Plot these points on the graph paper below. Use the X-axis for the angles and the Y-axis for the corresponding instantaneous voltages.



The teacher needs to check your work at this point...

8. **Turn off the AC power supply.**

9. Set up the DMM for measuring AC current.

   Note: The current is small so use the "mA" setting. You'll also need to press the SELECT button to adjust the meter for measuring AC current instead of DC current. And you'll also need to move the red probe's lead to the "mA" socket.

10. Wire the circuit of Figure 1 but don't turn it on.

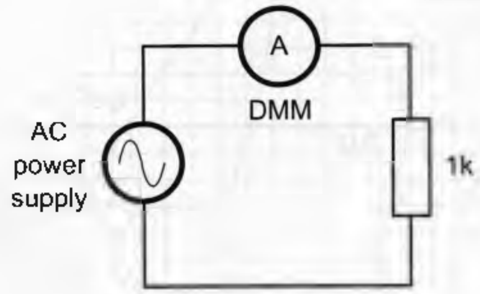


Figure 1

11. **Call the teacher to check your wiring BEFORE turning on the AC power supply.**

12. Turn on the power supply.

13. Measure and record the circuit current.

    Circuit current: 18.45 mA

Question 6
What are the disadvantages of measuring AC voltages and currents using a multimeter? **Tip:** What doesn't the meter tell you about the AC voltage you're measuring?

Dmm measures RMS voltage NOT Peak to peak. They DO NOT Show waveform Shape, frequency, or any distortion in signal.
Dmm will not show if AC is a perfect Sine wave

The teacher needs to check your work at this point...

Review questions

Answer these questions to check your understanding of what you have learnt for this chapter. Doing this will also help to prepare you for the tests.

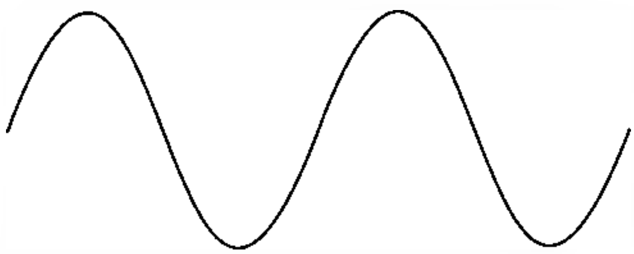
Tick the correct box

1. All AC waveforms have currents that

- ☐ don't change.
- ☐ increase indefinitely.
- ☐ reverse direction.
- ☐ decrease indefinitely.

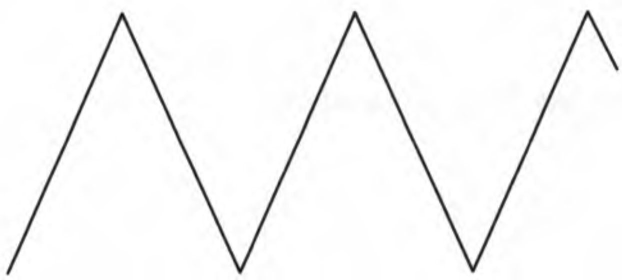
2. Name the following AC waveforms:

(a)



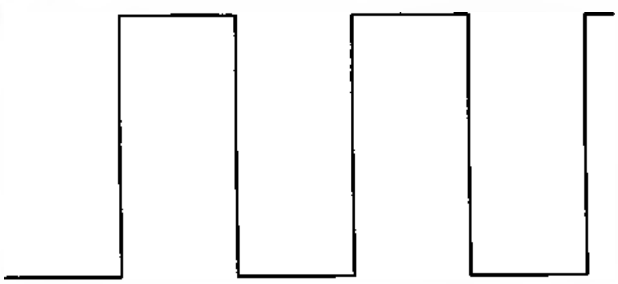
____

(b)



____

(c)



____

3. What is the name for the part of an AC waveform that is repeated?

- ☐ Cycle
- ☐ Unit
- ☐ Instant
- ☐ Peak

4. For each of the waveforms in the previous page, indicate one complete cycle.

5. What is the unit of measurement for the period of AC waveforms?

- ☐ Ohms
- ☐ Seconds
- ☐ Hertz
- ☐ Volts

6. The period of an AC waveform is

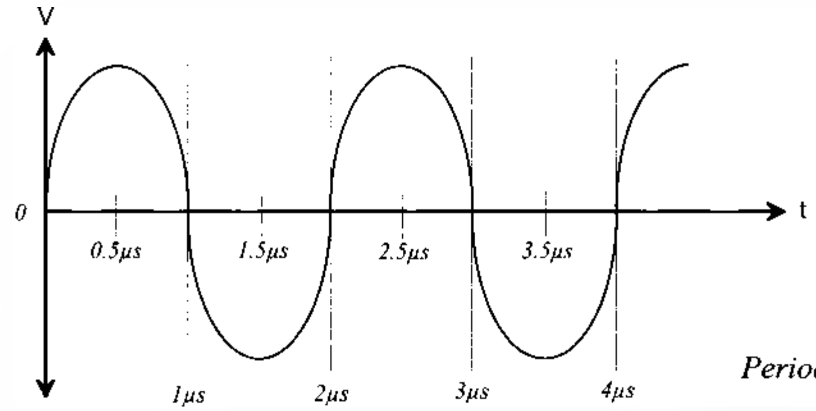
- ☐ the time it takes to complete one cycle.
- ☐ the number of cycles per second.
- ☐ the same as the frequency.
- ☐ the number of cycles per hour.

7. How many degrees are there in one cycle of an AC waveform?

- ☐ 0°
- ☐ 90°
- ☐ 180°
- ☐ 360°

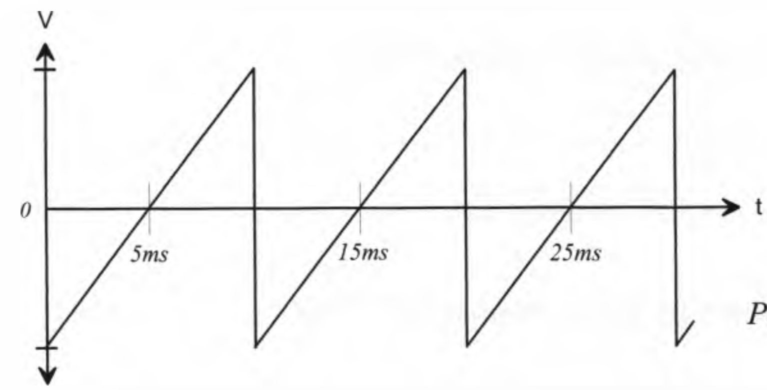
8. What is the period of the following AC waveforms

(a)



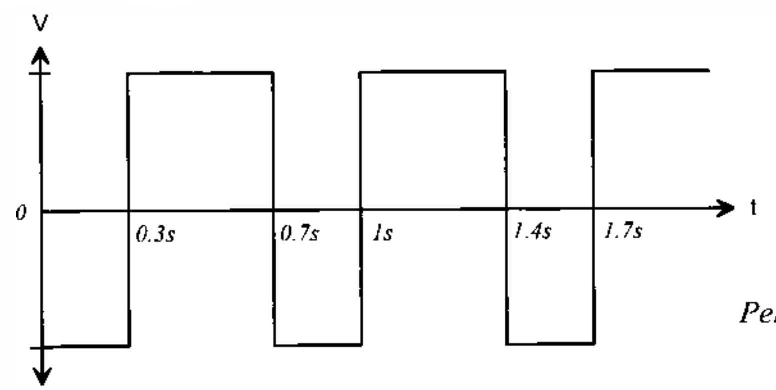
Period = ________

(b)



Period = ________

(c)



Period = ________

9. What is the unit of measurement for the frequency of AC waveforms?

- ☐ Ohms
- ☐ Seconds
- ☐ Hertz
- ☐ Volts

10. The frequency of an AC waveform is

- ☐ the time it takes to complete one cycle.
- ☐ the number of cycles per second.
- ☐ the same as the frequency.
- ☐ the number of cycles per hour.

11. What is the frequency of a sinewave with a period of 50µs?

____

____

12. What is the period of a squarewave with a frequency of 250Hz?

____

____

13. How many complete cycles of a 15kHz sinewave occur in 1.5ms?

____

____

____

____

14. What is the name used for the voltage indicated in Figure 1 below?

- ☐ Peak
- ☐ RMS
- ☐ Average
- ☐ Peak-to-peak

15. What is the name used for the voltage indicated in Figure 2 below?

- ☐ Peak
- ☐ RMS
- ☐ Average
- ☐ Peak-to-peak

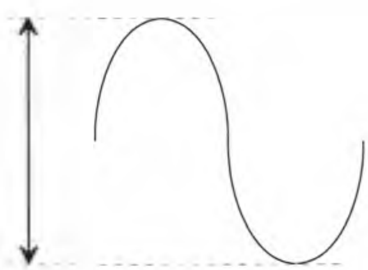


Figure 1

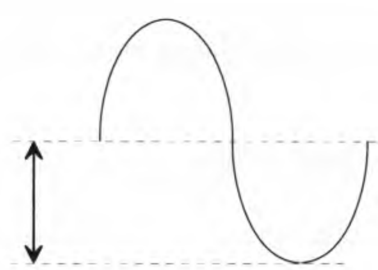


Figure 2

16. What's another name for references to the peak and peak-to-peak voltage of an AC waveform?

- ☐ Multitude
- ☐ Latitude
- ☐ Amplitude
- ☐ Vicissitude

17. An AC value simply written as 150V is assumed to be the

- ☐ peak value.
- ☐ RMS value.
- ☐ average value.
- ☐ peak-to-peak value.

18. What is the significance of the *root mean square* (RMS) value of an AC voltage?

19. Calculate the following for a 420Vp-p sinewave:

(a) the peak voltage

(b) the RMS voltage

20. Calculate the following for a 150V sinewave:

(a) the peak voltage

(b) the peak-to-peak voltage

21. What is the instantaneous voltage of a 85Vp-p sinewave at the following angles:

(a) 45°

(b) 90°

(c) 145°

(d) 300°

22. What is the instantaneous voltage of a 18Vp-p 2kHz sinewave 200µs after the beginning of the wave?

23. What are two limitations of using meters when measuring AC waveforms?

Student notes

Section 3 Using the oscilloscope

Purpose To develop your skills so that you can operate a cathode ray oscilloscope (CRO) and use it to measure AC and DC voltages.

Objectives At the end of this section you should be able to:

- List the advantages of using an oscilloscope over a multimeter to measure AC voltages
- Explain the purpose of commonly used oscilloscope controls
- Set up an oscilloscope in readiness to make DC or AC voltage measurements
- Use an oscilloscope to measure the size of DC voltages
- Use an oscilloscope to measure the amplitude and duration of AC waveforms

Oscilloscope controls

The following is a brief description of the controls on most oscilloscopes and some of their other important elements and features. The circled numbers are references to pictures in Appendix 2.

Elements/features

Cathode ray tube (CRT)	The CRT is like the picture tube in a television set. It fires an electron beam at the screen's face to produce a spot of light. By moving the spot of light left to right and up and down waveshapes are formed.
Trace	The trace is the path of the moving spot of light across the CRT's face. If the spot of light moves quickly enough the trace is a line.
Graticule	The graticule on the CRO is made up of the horizontal and vertical lines on the CRT's screen. The graticule is used together with the settings of the *Vertical Attenuation* and *Horizontal Sweep* controls to measure voltage and time.
Calibration output	Inside the CRO is a circuit that makes a squarewave that is exactly 1Vp-pk (or 0.5Vpk-pk for the University CRO) at 1kHz. The squarewave is fed to the *Calibration Output*. This signal can be used to check that the CRO's inputs are calibrated.

Controls

Intensity ⓪	Adjusting the *Intensity* varies the brightness of the trace on the CRO's screen.
Focus ①	Adjusting the *Focus* varies the sharpness of the trace on the CRO's screen.
Horizontal sweep or **Sweep time/division control** or **Timebase** ②	The *Horizontal Sweep* control adjusts the speed of the electron beam as it moves from left to right across the screen. The settings around the knob tell you how much time it takes the trace to move one whole division of the graticule. If the sweep rate is slow (eg 0.5s/div) then the trace is a moving spot. When the sweep rate is increased to about 2ms/div, the moving spot forms a line.

Variable horizontal sweep
❷

This is the red (or blue) knob inside the *Horizontal Sweep* control. For normal use of CROs this control should be in the "detent" (locked) position.

When the *Variable Horizontal Sweep* control is engaged (usually by turning it anti-clockwise out of the detent position) the sweep rate can be changed to rates other than those specified around the *Horizontal Sweep* knob. However, this means that the graticule is no-longer calibrated to the setting of the *Horizontal Sweep* control (the time/div) so the setting cannot be used for measuring absolute values of time.

Turning *Variable Horizontal Sweep* anti-clockwise increases the sweep rate.

Horizontal position
③

Turning this control anti-clockwise moves the whole trace to the left of the screen. Turning this control clockwise moves the whole trace to the right.

Horizontal magnification
or
×5 mag control
③

The *Horizontal Magnification* control is usually engaged by pulling the *Horizontal Position* knob out. It instantly increases the sweep rate by a factor of 5 (or 10 depending on the CRO). This means that you must divide the horizontal sweep setting by 5 (or 10) when calculating the period.

Vertical position
④

Turning this control anti-clockwise moves the trace up the screen. Turning this control clockwise moves the trace down the screen.

Vertical attenuation
⑤

If an input signal is too large, the top and bottom of it will not fit on the screen (that is, the vertical deflection is too great). The *Vertical Attenuation* reduces the input signal's size so that it can fit on the screen.

There are two *Vertical Attenuation* controls, one for each channel (or input). The settings around the knob tell you what each whole vertical division on the graticule represents as a voltage.

Variable vertical attenuation
❺

This is the red (or blue) knob inside the *Vertical Attenuation* control. For normal use of CROs this control should be in the "detent" (locked) position.

When the *Variable Vertical Attenuation* control is engaged (usually by turning it anti-clockwise out of the detent position) the attenuation of the input signal can be changed to levels other than that specified around the *Vertical Attenuation* knob. However, this means that the graticule is no-longer calibrated to the setting of the *Vertical Attenuation* control (the time/div) so the setting cannot be used for measuring absolute values of amplitude.

Turning *Variable Vertical Attenuation* anti-clockwise increases the attenuation.

Input coupling
⑥

There are two *Input Coupling* controls, one for each channel. They have three settings: *AC*, *GND* and *DC*. When set to the *GND* position the input signal is disconnected from the CRO (internally). Instead, the input to the CRO is connected directly to ground. This helps you to find the zero position on the screen.

When the *Input Coupling* is set to the *DC* position, the input signal is directly connected to the CRO and so the trace responds to all input signals (both AC and DC).

When the *Input Coupling* is set to the *AC* position, the input signal is connected to the CRO via a capacitor. This means that the trace only moves up or down in response to AC signals. DC signals are ignored because capacitors block DC.

Mode
⑦

This control allows the user to view the channel 1 input on its own, the channel 2 input on its own or both inputs at the same time. Viewing both inputs at the same time is used to compare signals.

Auto-triggering
⑧

Auto triggering is usually engaged by pulling out the *Trigger Level* knob. This ensures that there is a trace on the screen if the *Trigger Level* is not set correctly or even if there is no input signal.

Triggering level
⑧

Adjusting the *Triggering Level* control varies the point on the input signal where the trace starts its sweep across the screen. Care must be taken not to turn this control too much left or right otherwise the trace becomes unstable.

Trigger synchronisation
or
Sync
or
Slope
⑨

The *Sync* control is part of the triggering circuitry. For normal operation, it should be switched to either the "+" or "-" setting and determines whether the trace starts on the input signal's rising or falling edge.

The control has two other settings that can be used when looking at signals in television circuits.

Trigger source
or
Source
⑩

The *Trigger Source* control is also part of the triggering circuitry. For normal operation, it should be switched to the setting that matches the channel that you're input signal is connected to.

So, for example, if you're input signal is connected to the channel 1 input, the *Trigger Source* must be set to the *CH1* position. If you're input signal is connected to channel 2, the *Trigger Source* must be set to *CH2*.

However, for signals connected to both inputs, you can set the *Trigger Source* to either position. Practice will help you decide which is the better setting to use in each situation.

The *Trigger Source* control allows you to trigger the CRO using a signal other than one of the signals connected to the inputs. Options usually include: the *Line* position so that the triggering circuitry is sampling mains or the *EXT* position so that the triggering circuitry is sampling a signal that you fed it via the *EXT TRIG* input.

Setting up a 15MHz dual channel oscilloscope

There is no one rule about setting up CROs for taking voltage measurements because the procedure can vary a little or a lot depending on what it is you want to measure and the CRO that you're using. Furthermore, when taking measurements with a CRO you will end up changing the setting of many controls.

That said, the following procedure explains how to set up the *Trio 1560A* as a starting point for taking measurements in the practical exercises. An almost identical procedure is used for the *University-Paton OS-620* mounted on the benches in some of the classrooms.

Note: This procedure is so important that you will be tested on it in the first practical exam (so be prepared!).

General settings

1. Rotate the *Intensity* control to about three quarters of the way to fully-clockwise.
2. Set the *Mode* control to the *CH1* position (or the *CHA* position on the OS-620).

Vertical controls

1. Set the channel 1 *Input Coupling* control (or channel A on the OS-620) to the *AC* position.
2. | If you're using the Trio CRO... | If you're using the OS-620... |
   |---|---|
   | Rotate the channel 1 *Vertical Attenuation* control (the volts/div rotary switch) to the 0.2V/div setting. | Rotate the channel A *Vertical Attenuation* control to the 0.1V/div setting. |
3. Make sure that the *Vertical Attenuation Calibration* control is in the detent (locked) position.
4. Rotate the channel 1 *Vertical Position* control (or channel A on the OS-620) so that it is half way to fully-clockwise.

Horizontal controls

1. Rotate the *Horizontal Sweep* control (the sweep time/div rotary switch) to the *0.2ms* setting.
2. Make sure that the *Horizontal Sweep Calibration* control is in the detent position.
3. Rotate the *Horizontal Position* control to about half way to fully-clockwise.

Triggering controls

1. Pull out the *Triggering Level* control so that *AUTO-TRIGGERING* is activated.

2. Rotate the *Triggering Level* control so that is half way to fully clockwise.

	If you're using the Trio CRO...	If you're using the OS-620...
3.	Set the *Sync* switch to the "+" position.	Set the *Slope* switch to the "+" position.
4.	Adjust the *Source* switch to the *CH1* position	Set the *Sync* switch to the *AC* position.
5.	Skip this step.	Set the *Source* switch to the *INT* position.

Getting started

1. Turn on the CRO and let it warm up. After a minute a trace should appear on the screen.

   If not, check that you've set all of the controls correctly. If you still don't get a trace, call the teacher.

2. Adjust the *Intensity* knob so that the trace is not too bright.

3. Adjust the *Focus* knob so that the trace is a sharp line.

4. Plug a BNC to alligator-clip lead into the *CH1* input (or the *CHA* input on the OS-620).

5. Connect the BNC lead's red alligator-clip to the CRO's *CAL* output. A square wave should appear on the screen.

   To determine whether the CRO is calibrated, check that the squarewave is 5 divisions from peak to peak and that one cycle is 5 divisions long.

6. Finally, if you're going to be measuring DC voltages, set the channel 1 *Input Coupling* control to the *DC* position. Otherwise, leave it as is.

Measuring the peak-to-peak voltage of a waveform

To measure the peak-to-peak voltage of a signal on a CRO follow the procedure below.

1. Adjust the *Vertical Attenuation* control (the volts/div knob) so that the signal you want to measure is as big as it can be on the screen without being too big (see Figure 1c below).

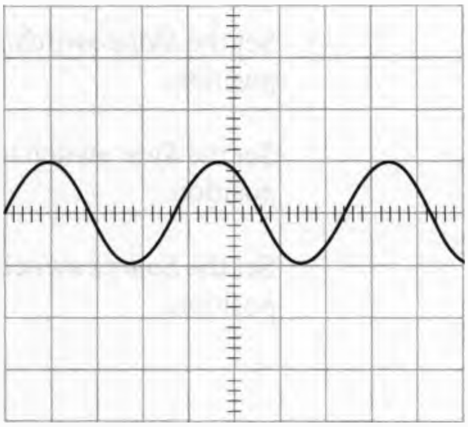


Figure 1a
The input signal is too small to make an accurate measurement

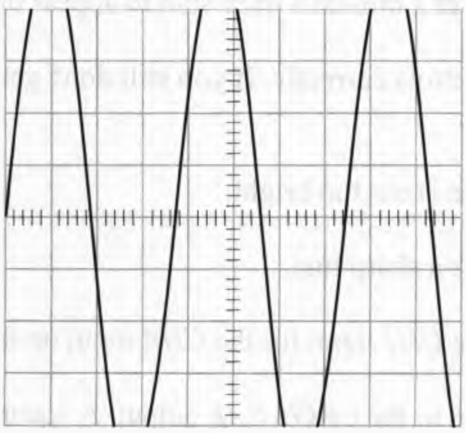


Figure 1b
The input signal is too big to make any kind of a measurement

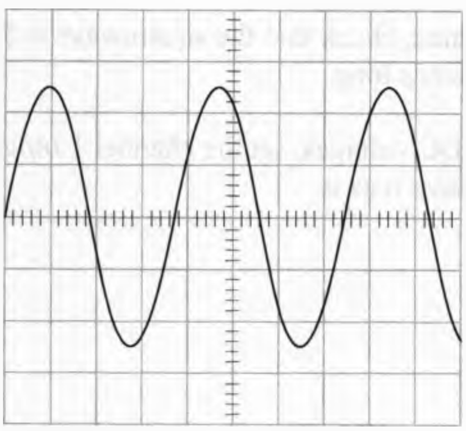


Figure 1c
The input signal is just right!

2. Adjust the *Vertical Position* control to align the waveform's lower peaks with one of the graticule's horizontal lines (see Figure 2).

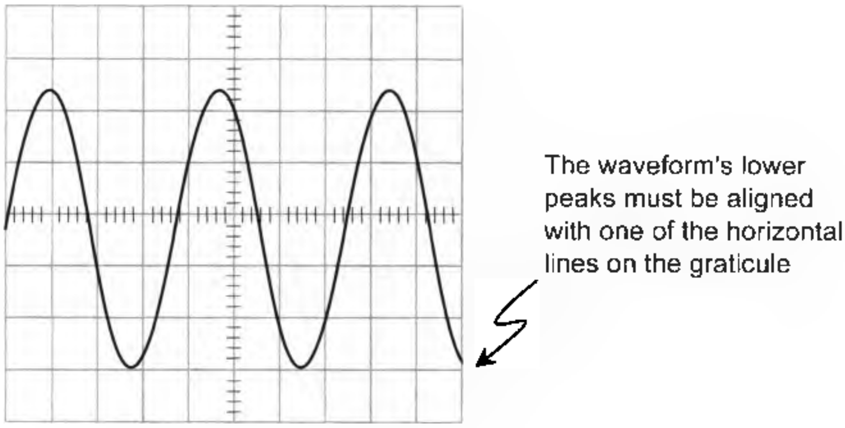


Figure 2

3. Adjust the *Horizontal Position* control to align one of the upper peaks with the graticule's centre vertical line (see Figure 3).

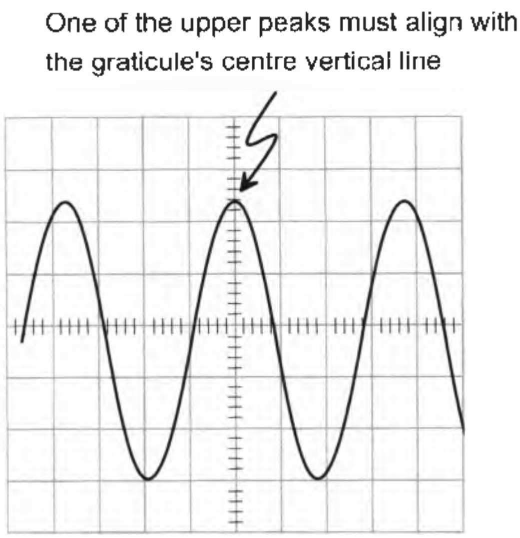


Figure 3

4. Count the number of divisions from the horizontal line that the lower peaks touch to the horizontal line that the upper peak touches (see Figure 4). Note: Each sub-division is worth **0.2** of a division.

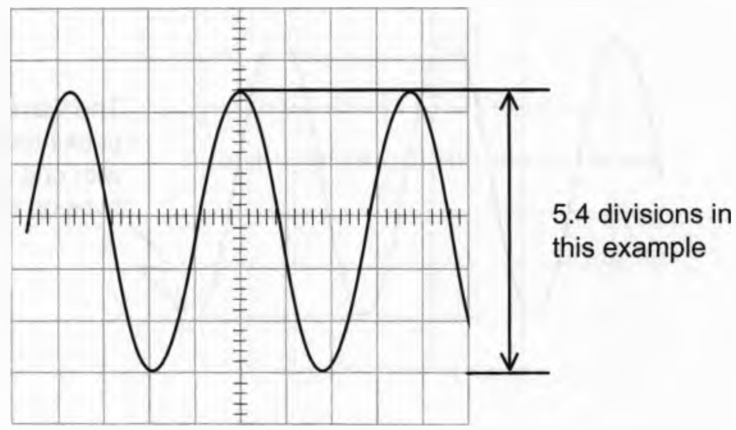


Figure 4

5. Multiply the number of divisions by the *Vertical Attenuation* control's setting.

   For example, if the *Vertical Attenuation* setting is 20mV/division, the peak-to-peak voltage of the signal in Figure 4 is:

$$V = 5.4 \times 20mV$$

$$V = 108mV_{pp}$$

Practise determining the peak-to-peak voltage of a signal by trying the following question.

1. What is the peak-to-peak voltage of the sinewave in Figure 5 below if the *Vertical Attenuation* control is set to 0.1V/division?

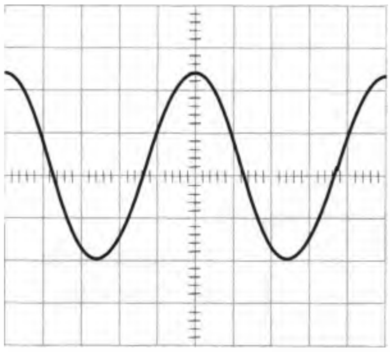


Figure 5

Measuring the peak voltage of a waveform

To measure the peak voltage of a signal on a CRO follow the procedure below.

1. Adjust the *Vertical Attenuation* control (the volts/div knob) so that the signal you want to measure is as big as it can be on the screen without being too big.

2. Set the *Input Coupling* control to the *GND* position.

3. Adjust the *Vertical Position* control so that trace aligns with the graticule's centre horizontal line (see Figure 6).

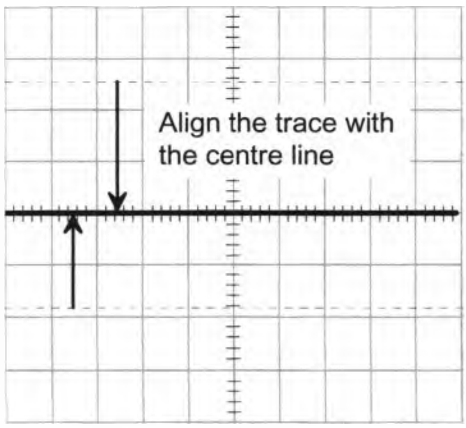


Figure 6

4. Set the *Input Coupling* control to the *AC* position.

5. Adjust the *Horizontal Position* control to align the peak that you want to measure with the centre vertical line on the graticule.

6. Count the number of divisions from the centre line to the horizontal line that the peak touches (see Figure 7).

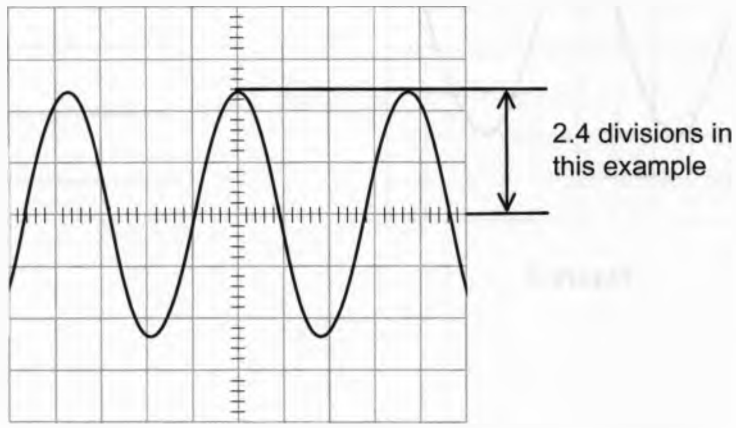


Figure 7

7. Multiply the number of divisions by *Vertical Attenuation* control's setting.

   For example, if the *Vertical Attenuation* setting is 5V/division, the peak voltage of the signal in Figure 7 is:

$$V = 2.4 \times 5V$$

$$V = 12V_p$$

Measuring the period of a waveform

To measure the period of a signal on a CRO follow the procedure below.

1. Adjust the *Horizontal Sweep* control (the seconds/div knob) so that one cycle of the input signal fills as much of the screen as possible without being too spread out (see Figure 8c below)

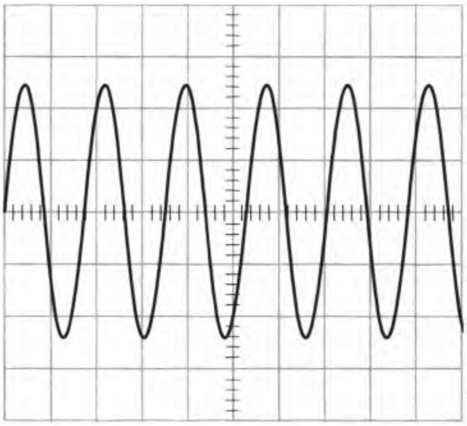


Figure 8a
There are too many cycles of the input signal on the screen

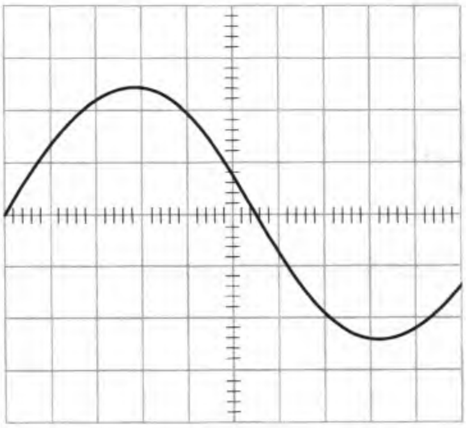


Figure 8b
There's not a whole cycle of the input signal on the screen

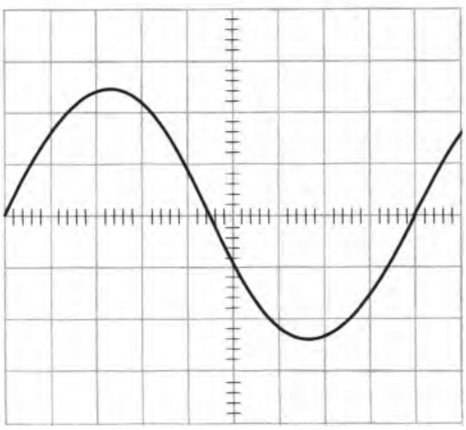


Figure 8c
The input signal is just right!

2. Adjust the *Vertical Attenuation* control (the volts/div knob) so that the signal you want to measure is as big as it can be on the screen without being too big.

3. Momentarily set the *Input Coupling* control to the *GND* position and adjust the *Vertical Position* control so that the trace aligns with the graticule's centre horizontal line.

4. Adjust the *Horizontal Position* control to align the point at which signal crosses the zero voltage line to the first vertical line on the graticule (see Figure 9).

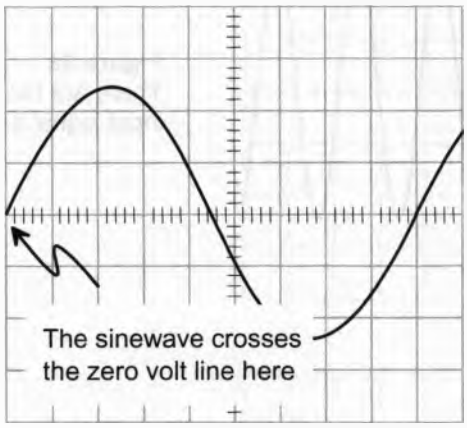


Figure 9

5. Count the number of divisions from the first vertical line to the vertical line where the cycle starts again (see Figure 10).

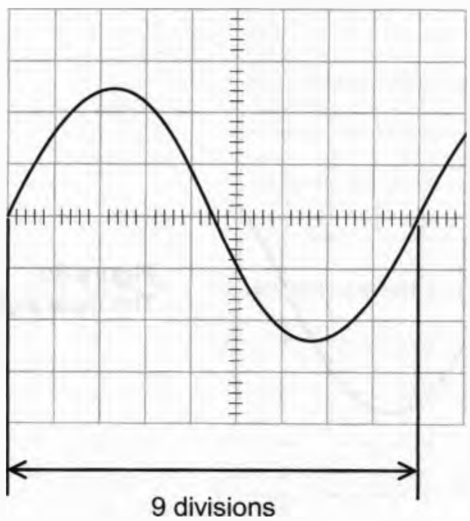


Figure 10

6. Multiply the number of divisions by the *Horizontal Sweep* control's setting.

   For example, if the *Horizontal Sweep* setting is 2ms/division, the period of the signal is:

$$Period = 9 \times 2ms$$

$$Period = 18ms$$

Practise determining the period of a signal by trying the following question.

1. What is the period of the sinewave in Figure 11 below if the *Horizontal Sweep* control is set to 0.5µs/division?

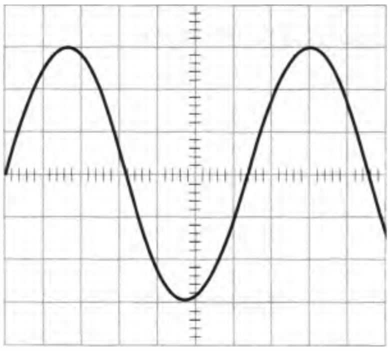


Figure 11

Measuring the frequency of a waveform

Importantly, the CRO cannot be used to directly measure the frequency of an AC signal. However, the frequency can be found by measuring the period (using the procedure described above) and converting it to frequency using the equation $f = \frac{1}{P}$.

Practise determining the frequency of a signal by trying the following question.

1. What is the frequency of the signal in Figure 11?

Measuring DC voltages

To measure a DC voltage on a CRO follow the procedure below.

1. Set the *Input Coupling* control to the *GND* position.

2. Adjust the *Vertical Position* control so that trace aligns with one of the graticule's horizontal lines (see Figures 12a and 12b). [Note: If you're measuring a positive voltage use a line at the bottom of the screen and if you're measuring a negative voltage then use a line at the top.]

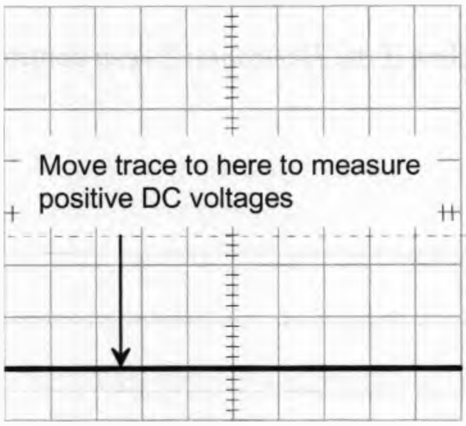


Figure 12a

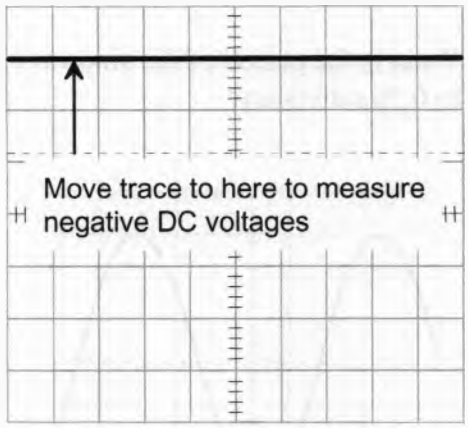


Figure 12b

3. Set the *Input Coupling* control to the *DC* position.

4. If the trace disappears then adjust the *Vertical Attenuation* control (the volts/div knob) anti-clockwise until the trace returns.

5. Count the number of divisions that the trace moves from the horizontal line that you aligned it to (see Figure 13).

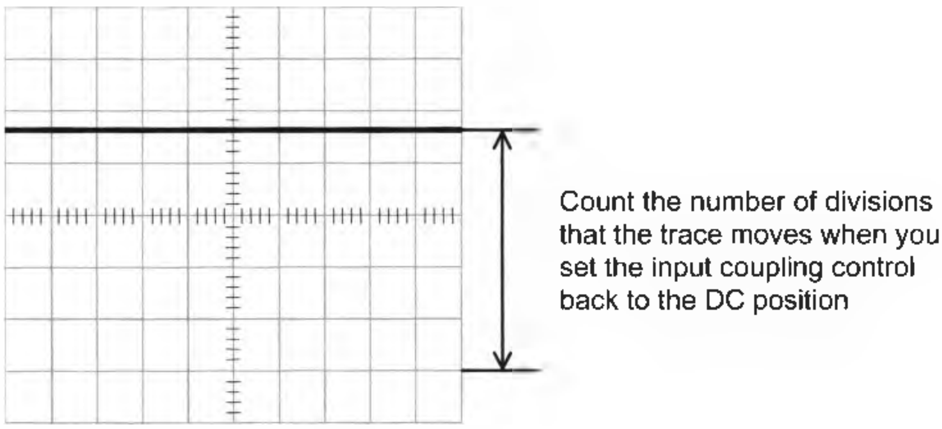


Figure 13

6. Multiply the number of divisions by the setting on the *Vertical Attenuation* control.

Student notes

Skill practice 3

Practise measuring DC and AC voltages and the period of AC waveforms using an oscilloscope

This exercise is practise for the sorts of skills you may be required to perform in a practical test. Remember, in any practical tests you will be working alone so make sure that you can perform all the steps. It should take you about 1 hour to complete this exercise.

Equipment

- dual output AC power supply
- digital multimeter
- two BNC to banana-plug leads

Remember:

Follow TAFE NSW WHS guidance at all times!

Work tasks

1. Read your WHS responsibilities at the top of the form below. Then conduct a WHS risk assessment and record your findings in the space provided.

Responsibilities of students under the Model WHS Act: s28

- Take reasonable care for your own health and safety by working safely at all times
- Take reasonable care to ensure that your acts or omissions don't put the health and safety of others at risk
- Follow all TAFE NSW WHS guidance and comply with all reasonable instructions from TAFE NSW staff to assist them in complying with the TAFE NSW WHS requirements
- In addition to the above, you must:
  - use and maintain machinery, tools and all other equipment properly and safely
  - ensure that your work area is free of hazards
  - notify a TAFE NSW staff member of actual or potential hazards
  - wear/use prescribed safety equipment
  - take notice of any safety signs and adhere to their instructions

Risks involved in this activity include:	**Control measures:**
Trip hazards (eg students bags) Objects dropped on feet (while equipment is taken to and from workbenches). Others: ______________________ ______________________ ______________________	Move bags and other objects from walkways Plan lifting of equipment Other: ______________________ ______________________ ______________________

My signature here indicates that I have read and understand my responsibilities under the Model WHS Act s28 (detailed above). I have also conducted a risk assessment before undertaking this activity and have identified measures to control these risks and have implemented them.

Signature: ______________________ Date: ______________

Part A - familiarising yourself with some of the controls

2. Gather the equipment needed for this exercise.

3. Identify the make and model of the CRO that you'll be using.

   Make: Model:

4. Set up the CRO and test its channel 1 input (or channel A on the OS-620) per the procedure on pages 3-6 and 3-7.

The teacher needs to check your work at this point...

5. When the teacher has checked that the CRO has been set-up correctly, switch the channel 1 *Input Coupling* control to the *DC* setting then disconnect the lead from the CRO's input.

6. Turn the channel 1 *Vertical Position* control both fully clockwise and fully anti-clockwise and observe the effect.

Question 1
What does the *Vertical Position* control do?

7. Adjust the *Vertical Position* control so that the trace is in the middle of the screen.

8. Turn the *Horizontal Position* control both fully clockwise and fully anti-clockwise and observe the effect.

Question 2
What does the *Horizontal Position* control do?

9. Adjust the *Horizontal Position* control so that the trace crosses the entire screen.

10. Push the *Triggering Level* knob in and observe the effect.

Question 3
What happens when *Triggering Level* control is not in the *AUTO* position?

____

11. Pull the *Triggering Level* knob back out.

12. Rotate the *Horizontal Sweep* control to the *0.5s* position and observe the effect.

13. Set the *Horizontal Sweep* control to the *0.2ms* position.

Question 4
What does the *Horizontal Sweep* control do?

____

The teacher needs to check your work at this point...

Part B - Measuring DC voltages

1. Turn on the bench-mounted DC power supply and adjust one of its outputs to 3V using the digital multimeter.

2. Adjust the *Vertical Attenuation* control to the *0.5V/div* setting.

3. Adjust the *Vertical Position* control so that the trace runs along the horizontal line second from the bottom of the graticule (as shown in Figure 1).

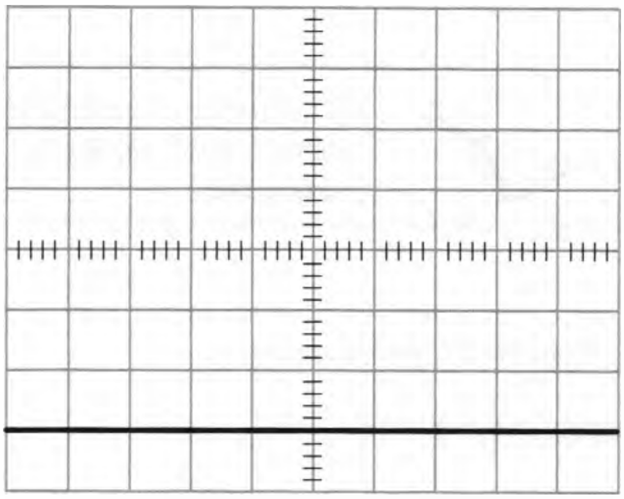


Figure 1

4. Reconnect the BNC to alligator-clip lead to channel 1 of the CRO.

5. Connect the BNC lead to the DC power supply's output that you set to 3V. Connect the red alligator-clip to the positive terminal and the black alligator-clip to the negative terminal.

6. Draw the trace's new position on the graticule in Figure 1 above.

Question 1
How many divisions has the trace moved from the original position?

Question 2
What voltage does this represent?

Question 3
Why does the voltage being measured just produce a straight line on the screen?

Question 4
Is the DC voltage positive or negative? How do you know?

The teacher needs to check your work at this point...

7. Disconnect the CRO from the DC power supply.

8. Set the DC power supply's output to 5V.

9. Reconnect the CRO to the power supply (see step 5 if you're not sure how to do this).

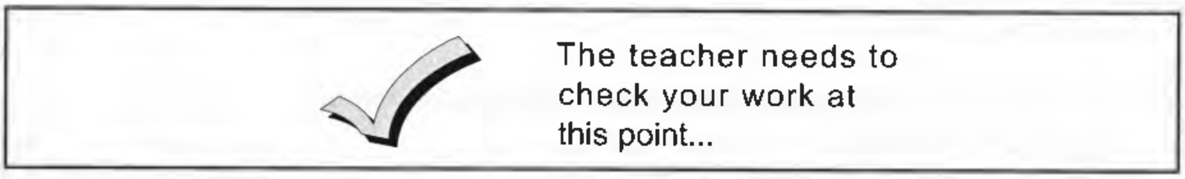
Question 5
Why has the trace disappeared?

10. Turn the *Vertical Attenuation* control (the volts/div rotary switch) to the *1V* setting.

Question 6
How many divisions has the trace moved from the zero position?

Question 7
Multiply the number of divisions by the *Vertical Attenuation* control setting. What's the voltage?

Question 8
What control on an analog multimeter is the *Vertical Attenuation* control like?



Part C - Measuring AC voltages

1. Disconnect the CRO from the DC power supply.

2. Set the *Vertical Attenuation* control to the *10V* setting.

3. Set the *Horizontal Sweep* control (the sweep time/dive rotary switch) to the *5ms* setting.

4. Set the channel 1 *Input Coupling* control to the *AC* setting.

5. Plug in and turn on the AC power supply.

6. Connect the CRO to one of the AC power supply's outputs. It doesn't matter which colour alligator-clip is connected to which terminal, just as long as one is connected to the yellow terminal and the other to the blue terminal on the same output.

7. Adjust the *Vertical Position* control so that the negative peaks of the waveform touch one of the graticule's horizontal lines.

8. Accurately draw what you observe on the screen of the CRO in the graticule of Figure 2.

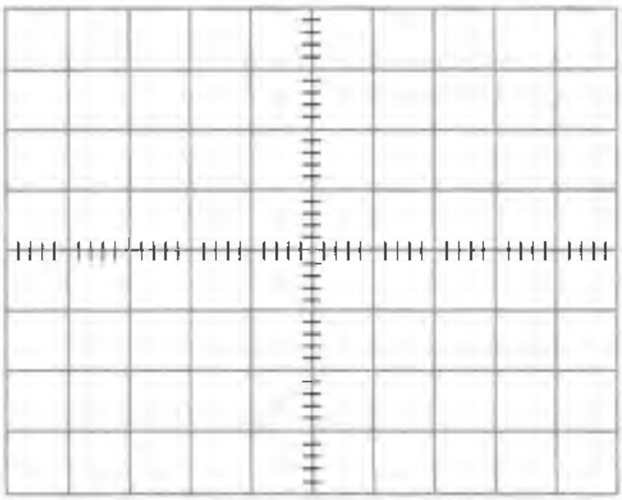
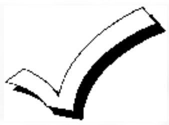


Figure 2

9. Count the number of divisions there are from the bottom of the waveform to the top of the waveform.

10. Use the number of divisions and the *Vertical Attenuation* setting to determine the peak-to-peak voltage of the sinewave.

Sinewave voltage is: ____________________



The teacher needs to check your work at this point...

11. Set the *Vertical Attenuation* control to the *20V* position.

Question 1
Has changing the *Vertical Attenuation* control's setting changed the size of the sinewave out of the AC power supply? Explain your answer.

Question 2
Which *Vertical Attenuation* setting - *10V* or *20V* - is the better one to use when measuring the sinewave's amplitude? Explain why.

12. Return the *Vertical Attenuation* to the *10V* setting.

13. Set the channel 1 *Input Coupling* control to the *GND* position and note the effect.

14. Adjust the *Vertical Position* control so that the trace is in the middle of the graticule.

15. Return the *Input Coupling* control to the *AC* position.

Question 3
What have you just done in steps 13, 14 and 15?

____

16. Count the number of divisions for one cycle (360°) of the sinewave.

17. Use the number of divisions and the *Horizontal Sweep* control's setting to determine the period of the waveform.

    Period of the sinewave is: _______________________________

Question 4
Calculate the frequency of the sinewave.

____

____

18. Set the *Horizontal Sweep* control to the *10ms* setting.

Question 5
Has changing the *Horizontal Sweep* control's setting changed the frequency of the sinewave out of the AC power supply? Explain your answer.

____

____

Question 6
Which *Horizontal Sweep* setting - *5ms* or *10ms* - is the better one to use when measuring the sinewave's period? Explain why.

____

____

The teacher needs to check your work at this point...

Part D - More advanced CRO adjustments

1. Return the *Horizontal Sweep* control to the *5ms* setting.

2. Set the *Sync* control to the "-" position and observe the effect (or set the *Slope* control on the OS-620 to the "-" position).

Question 1
What does the *Sync* control do?

3. Return the *Sync* control to the "+" setting.

4. Vary the *Triggering Level* control both clockwise and anti-clockwise by only a small amount and observe the effect.

Question 2
What does the *Triggering Level* control do?

5. Vary the *Triggering Level* control both fully clockwise and fully anti-clockwise and observe the effect.

Question 3
What happens if you turn the *Triggering Level* control too far to the left or right?

6. Set the *Triggering Level* control so that the zero point of the sinewave starts on the graticule's centre line.

7. Set the *Source* control to the *CH2* and *EXT* positions and observe the effect.

Question 4
What happens to the trace on the screen when the *Source* control is not set correctly? Explain why.

8. Return the *Source* switch to the *CH1* position (or *CHA* position on the OS-620).

9. Pull the *Horizontal Position* knob out and observe the effect.

Question 5
What function other than moving the trace left and right does the *Horizontal Position* knob control?

10. Push the *Horizontal Position* knob back in.

The teacher needs to check your work at this point...

Part E - Dual mode operation

1. Adjust the channel 2 (channel B) vertical controls as follows:

   (a) *Vertical Attenuation* to the *10V* setting

   (b) *Variable Vertical Attenuation* in the detent position

   (c) *Vertical Position* knob to the middle of its travel

   (d) *Input Coupling* to the *AC* position.

2. Set the *Mode* switch to the *DUAL* position.

3. You should now have two traces on the screen. If not, call the teacher.

4. Connect the other BNC to alligator-clip lead to the channel 2 input.

5. Connect channel 2 to the other output on the AC power supply and observe the effect.

6. Vary the *Vertical Position* knobs of both channels and observe the effect.

Question 1
What is the dual mode on the CRO useful for?

The teacher needs to check your work at this point...

Review questions

Answer these questions to check your understanding of what you have learnt for this chapter. Doing this will also help to prepare you for the tests.

1. What is the waveshape, typical voltage and frequency of the *CAL* output's signal?

- ☐ 5Vp-p sinewave at 1kHz
- ☐ 1Vp-p square wave at 5kHz
- ☐ 50Vp-p sinewave at 10kHz
- ☐ 0.5Vp-p square wave at 1kHz

2. What is the purpose of the *CAL* output?

____

____

____

3. What oscilloscope control would you adjust to change the display from Figure 1 to Figure 2?

- ☐ The *Horizontal Sweep* (*time/div*) control
- ☐ The *Horizontal Position* control
- ☐ The *Vertical Attenuation* (*volts/div*) control
- ☐ The *Vertical Position* control

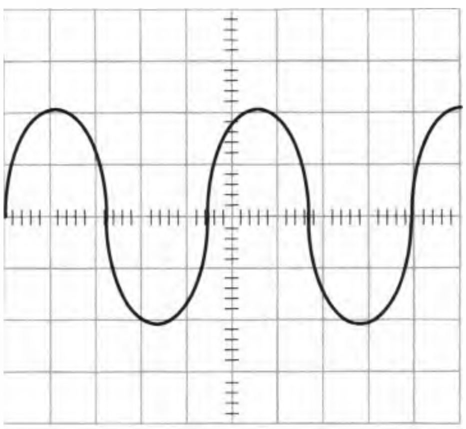


Figure 1

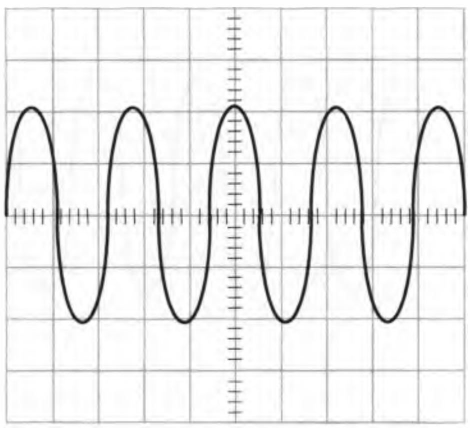


Figure 2

4. What oscilloscope control would you adjust to change the display from Figure 3 to Figure 4?

- ☐ The *Horizontal Sweep* (*time/div*) control
- ☐ The *Horizontal Position* control
- ☐ The *Vertical Attenuation (volts/div*) control
- ☐ The *Vertical Position* control

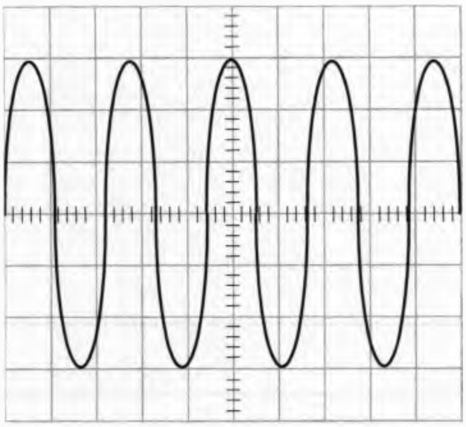


Figure 3

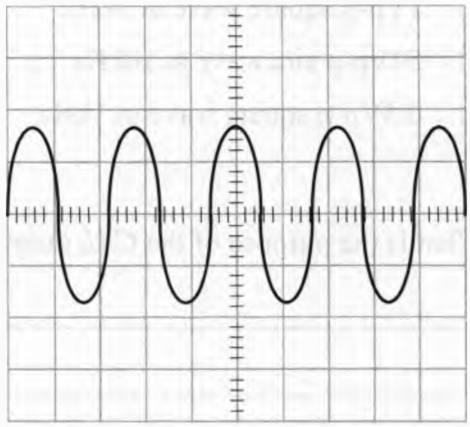


Figure 4

5. What oscilloscope control would you adjust to change the display from Figure 5 to Figure 6?

- ☐ The *Horizontal Sweep* (*time/div*) control
- ☐ The *Horizontal Position* control
- ☐ The *Vertical Attenuation (volts/div*) control
- ☐ The *Vertical Position* control

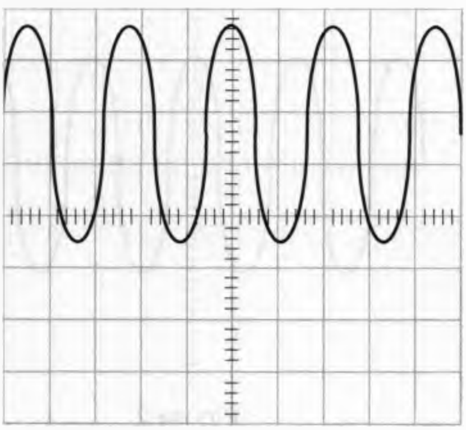


Figure 5

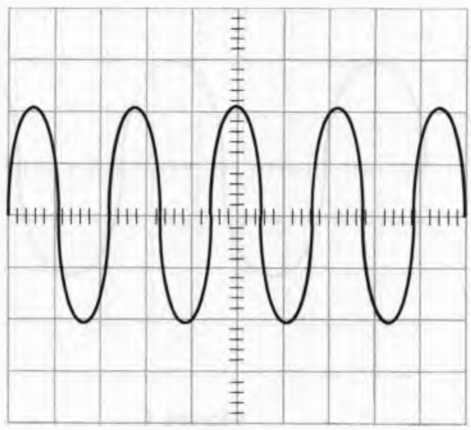


Figure 6

6. What oscilloscope control would you adjust to change the display from Figure 7 to Figure 8?

- ☐ The *Auto-triggering* control
- ☐ The *Mode* control
- ☐ The *Slope* control
- ☐ The *Trigger Level* control

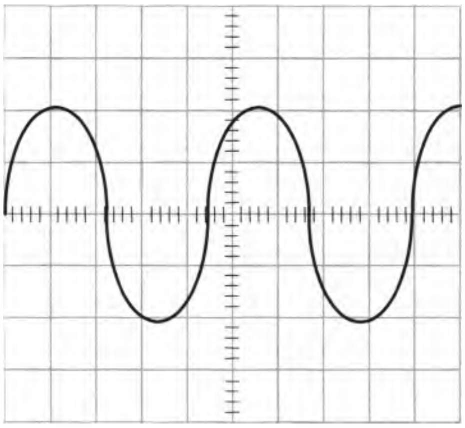


Figure 7

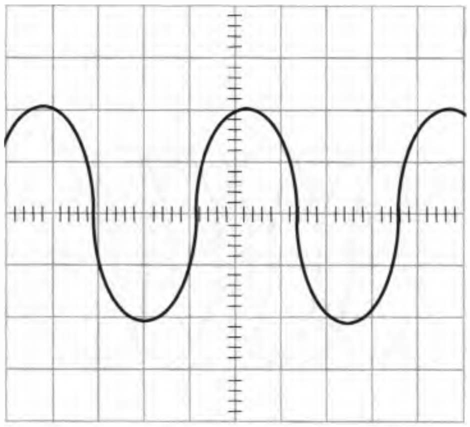


Figure 8

7. What oscilloscope control would you adjust to change the display from Figure 9 to Figure 10?

- ☐ The *Auto-triggering* control
- ☐ The *Mode* control
- ☐ The *Slope* control
- ☐ The *Trigger Level* control

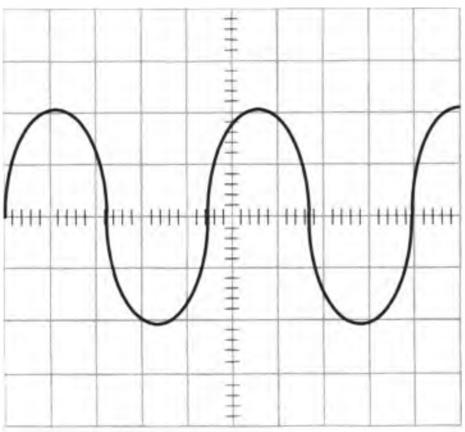


Figure 9

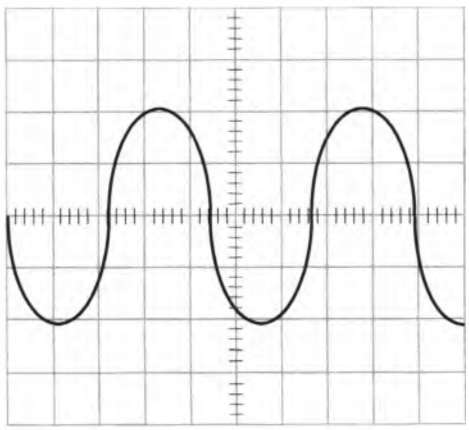


Figure 10

8. What CRO control can be adjusted when its display looks like Figure 11 and should look like Figure 12?

- ☐ The *Auto-triggering* control
- ☐ The *Mode* control
- ☐ The *Slope* control
- ☐ The *Trigger Level* control

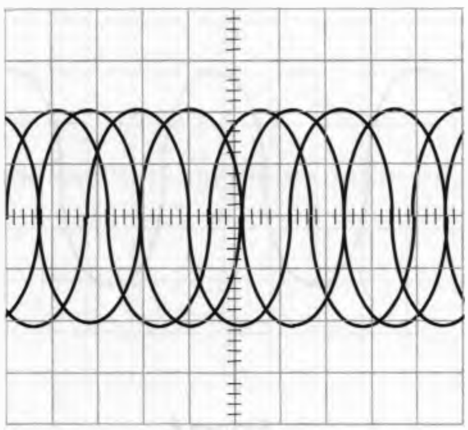


Figure 11

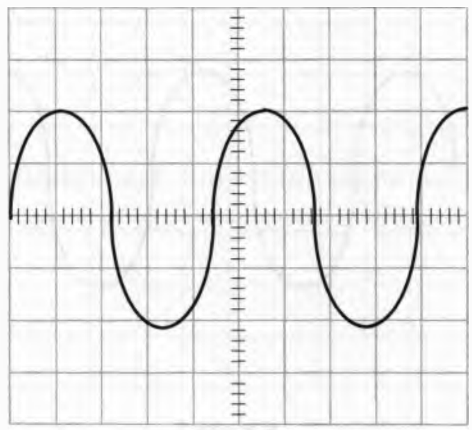


Figure 12

9. What control can be used to always give a flat line trace on a CRO's display?

- ☐ The *Auto-triggering* control
- ☐ The *Mode* control
- ☐ The *Slope* control
- ☐ The *Trigger Level* control

10. State the appropriate setting for each of the CRO controls listed below when you are about to use a CRO for the first time.

Intensity: ____________________

Mode: ____________________

Input Coupling: ____________________

Vertical Attenuation: ____________________

Vertical Attenuation Calibration: ____________________

Vertical Position: ____________________

Horizontal Sweep: ____________________

Horizontal Sweep Calibration: ____________________

Horizontal Position: ____________________

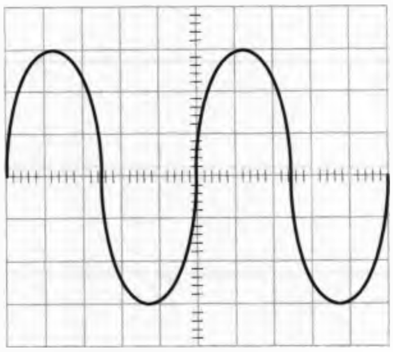
Triggering Level: ____________________ and ____________________

Sync: ____________________

Source: ____________________

11. Specify the peak-to-peak voltage, period and frequency for each of the following AC signals given the CRO control settings specified:

(a)



Vertical attenuation: 2V/div

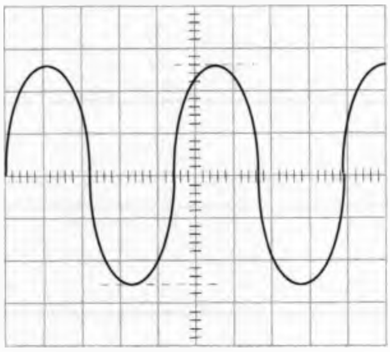
Horizontal sweep: 1ms/div

Vp-p: ______________

Period: ______________

Frequency: ______________

(b)



Vertical attenuation: 0.5V/div

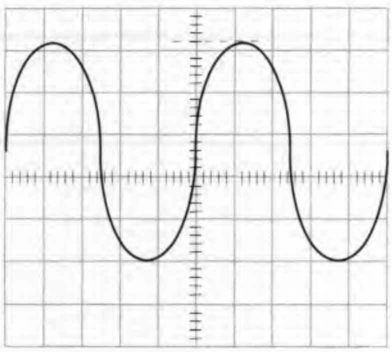
Horizontal sweep: 20ms/div

Vp-p: ______________

Period: ______________

Frequency: ______________

(c)



Vertical attenuation: 50mV/div

Horizontal sweep: 0.5μs/div

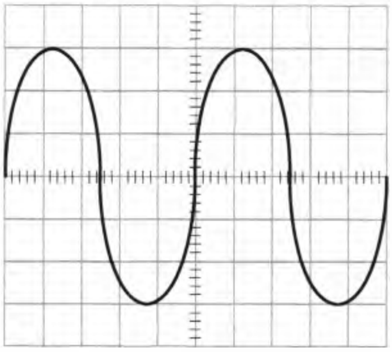
Vp-p: ______________

Period: ______________

Frequency: ______________

12. Specify the vertical attenuation and horizontal sweep settings that the CRO must have to display the following AC signals given the signal's specifications:

(a)



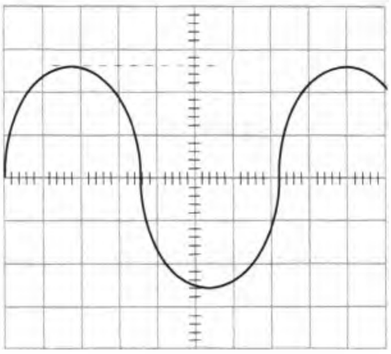
Peak-to-peak V: 120mV

Period: 2.5μs

Vertical attenuation: ____________ (volts/div)

Horizontal sweep: ____________ (secs/div)

(b)



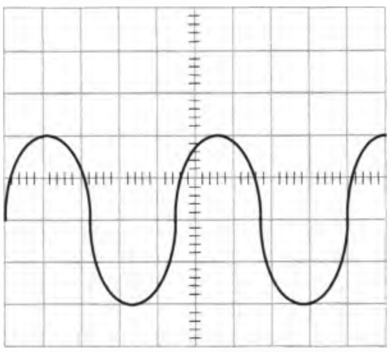
Peak-to-peak V: 26V

Period: 360μs

Vertical attenuation: ____________ (volts/div)

Horizontal sweep: ____________ (secs/div)

(c)



Peak-to-peak V: 200mV

Frequency: 45.45Hz

Vertical attenuation: ____________ (volts/div)

Horizontal sweep: ____________ (secs/div)

13. Figures 15 and 16 show the same signal displayed on two CROs. Which CRO is better set-up to measure the signal's peak to peak voltage? Explain why.

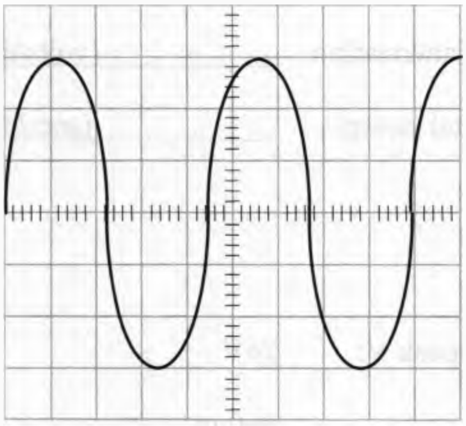


Figure 15

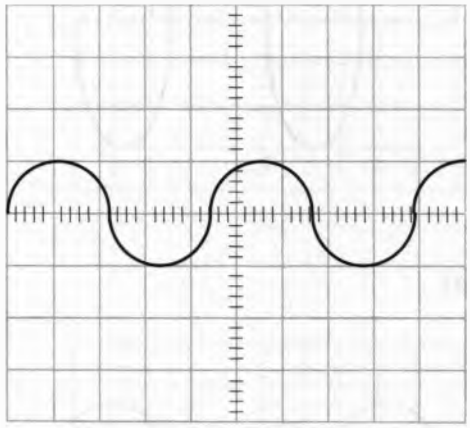


Figure 16

14. Figures 17 and 18 show the same signal displayed on two CROs. Which CRO is better set-up to measure the signal's period? Explain why.

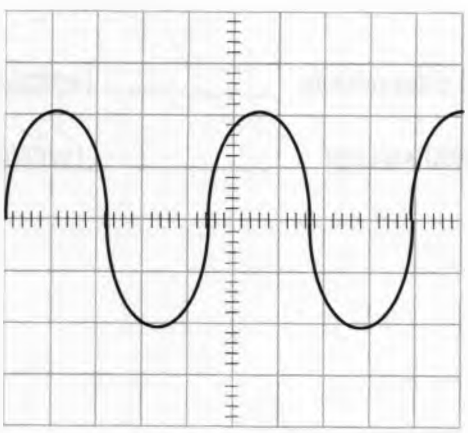


Figure 17

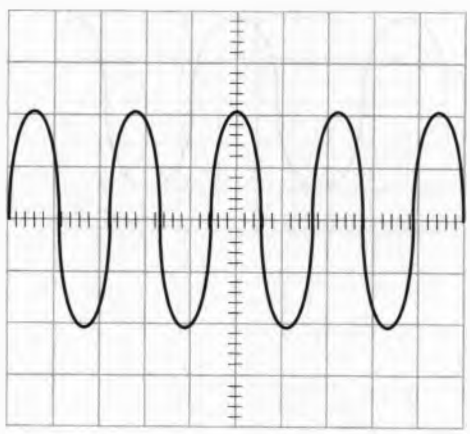


Figure 18

Section 4 Phase, measuring phase difference and phasors

Purpose To develop your ability to measure the phase difference between AC signals and to represent one or more sinewaves using phasors.

Objectives At the end of this section you should be able to:

- Define the terms *phase angle*, *in phase*, *out of phase*, *phase difference* and *phase shift* as applied to AC signals
- State the unit of measurement for phase difference
- Draw examples of two or more sinewaves that are out of phase by less than, more than and exactly 180°
- Measure the phase difference between two sinewaves using an oscilloscope
- Define the term *phasor*
- Draw the phasor diagram for two or more sinewaves that are in phase and out of phase with each other
- Explain the advantages of representing sinewaves using phasors

Introduction

When repairing electronics equipment, it's common for technicians to measure AC waveforms and compare them to what is expected. The CRO is the main piece of test equipment used for this purpose and the notes in the previous section explain how to use one to measure several key AC attributes.

It's also sometimes necessary for technicians to compare waveforms at different points in the circuit to see whether or not they're synchronised to each other. That is, technicians often need to know if the waveforms go up and down at exactly the same time as each other. Sometimes the signals can be out of step and, when this happens, it can be important to know by how much. This section shows you how to use a CRO to measure this and introduces you to an AC analysis tool called *phasor diagrams*.

Terminology

There are several terms used by electronics technicians when talking about the relationship between waveforms in terms of synchronisation. The following notes list and explain them.

Phase

The word *phase* simply means "stage" or "point". You've probably heard this term before. When organisations make big changes, they often "phase them in" meaning that they're introduced in stages. There are "phases of the moon" which is a reference to the different stages of the moon's cycle (eg new-moon, quarter-moon, full-moon, three-quarter moon and old-moon).

All AC signals have phases as well. Two big phases are the *positive half-cycle* and the *negative half-cycle* and they're shown in Figure 1 below using a sinewave.

Figure 1 *Two phases of a sinewave*

By definition, any point in an AC waveform is also a phase. That being the case, all instantaneous values of an AC waveform are phases.

Phase angle

Recall that the position of an instantaneous voltage or current can be designated using an angle between 0° and 360°. The angular position of instantaneous voltages/currents are known as *phase angles*. An example of one is shown in Figure 2 below where the instantaneous value indicated has a phase angle of 125°.

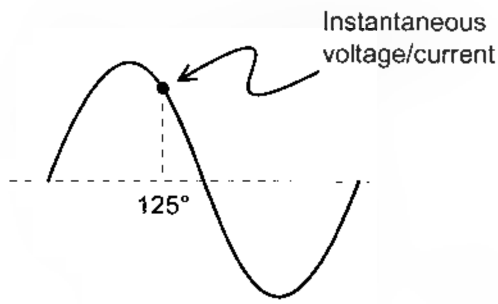


Figure 2 *The instantaneous voltage/current indicated has a phase angle of 125°*

Phase relationship

The *phase relationship* of two or more signals refers to whether the signals go up and down at the same time. When two AC waveforms cross the zero line and reach their peaks at exactly the same time, they're said to be *in phase* with each other. Figure 3 below shows two identical sinewaves that are in phase.

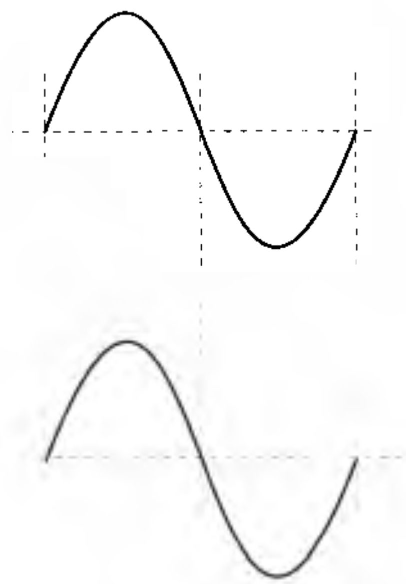


Figure 3 *Two identical sinewaves that are in phase*

When AC waveforms don't cross the zero line and reach their peaks at exactly the same time they're said to be *out of phase*. Figure 4 shows a pair of identical sinewaves that are out of phase (they've been drawn on the same 0V line so you can better see the difference).

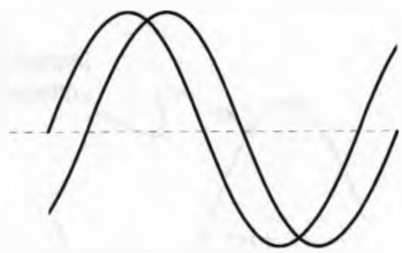


Figure 4 *Two signals that are out of phase with each other*

Leading and lagging

If you think of a race, the person that crosses the half-way mark first is said to "lead" the other competitors. It could also be said that the other competitors "lag" the person that crossed the half-way mark first.

Similarly, when AC waveforms are out of phase, one waveform is said to lead and the others lag. In the example in Figure 5 below, sinewave A *leads* sinewave B because it crosses the zero line and reaches its peaks before sinewave B. Conversely, sinewave B *lags* sinewave A because it crosses the zero line and reaches its peaks after sinewave A.

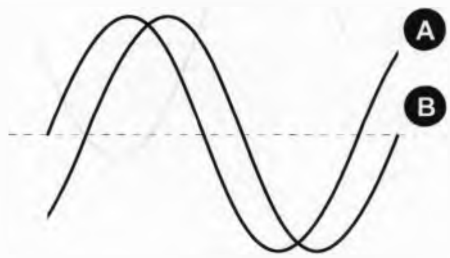


Figure 5 *Sinewave A leads sinewave B*

If you find it tricky to work out which waveform leads and which is lags, use this trick to help you. When writing the word "race", the letter *r* is written first so it leads the other letters. Importantly, *r* is physically situated to the left of the other letters. Similarly, a waveform that reaches its peaks to the left of other waveforms leads them.

Phase shift
Most circuits in electronics have at least one input and one output. When an AC waveform is connected to a circuit's input, the waveform travels through the circuit and instantly appears at the output. It's common for most circuits to process the waveform and change it in some way. For example, amplifiers make the waveform bigger. It is also common for circuits to change the phase relationship of the waveform. This is called a *phase shift*. Sometimes the phase shift is desirable, sometimes it's not.

Phase difference
AC waveforms aren't always out of phase by the same amount. The term *phase difference* is the name for the amount that two (or more) AC waveforms are out of phase. Figures 6a and 6b below show two pairs of sinewaves with different phase differences.

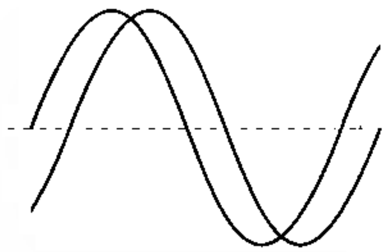


Figure 6a

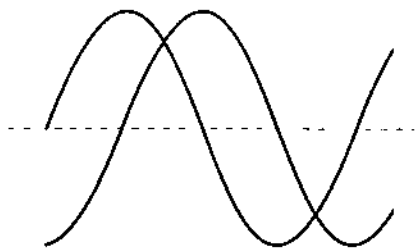


Figure 6b

As you will learn in later modules, the size of the phase difference between two AC waveforms can be very important. Consequently, a method of quantifying phase difference is necessary.

Quantifying phase difference

An obvious method of quantifying phase difference is to use *time*. After all, people use this method a lot (especially in sprint races). Figure 7 below shows two 1kHz sinewaves with one of them lagging the other by 250μs.

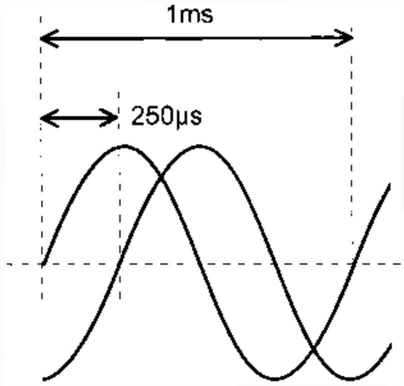


Figure 7 *Two 1kHz sinewaves with one lagging the by 250μs*

At first glance, quantifying the phase difference using *time* seems reasonable. However, it has a problem. Pairs of AC waveforms with the same relative phase difference can be out of phase by different amounts. Conversely, pairs of AC waveforms with a different relative phase difference can be out of phase by the same amount.

To explain, consider Figures 8a and 8b below. Figure 8a shows two 1kHz sinewaves with one lagging the other by 250μs. Figure 8b shows two 10kHz sinewaves with a phase difference that is clearly proportionally the same as the 1kHz sinewaves. However, as the period of the two 10kHz sinewaves is 100μs, the time lag between them is 25μs and not 250μs.

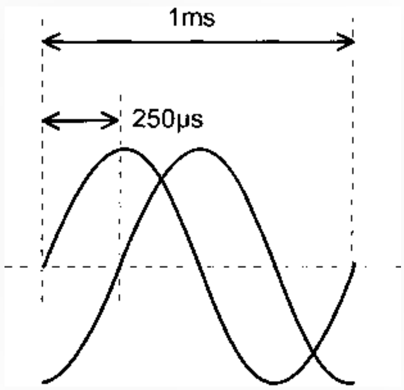


Figure 8a

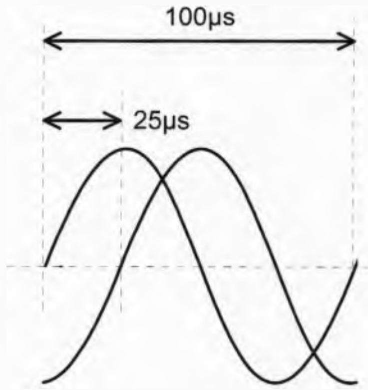


Figure 8b

A better method of quantifying the phase difference between two waveforms is to express the difference as a fraction of their period. For example, the phase difference between the pairs of sinewaves in Figures 8a and 8b is:

Figure 8a: $\frac{250\mu s}{1ms} = 0.25$

Figure 8b: $\frac{25\mu s}{100\mu s} = 0.25$

Quantifying phase difference this way is an improvement because the resulting figure is independent of the waveforms' period/frequency. That is, a phase shift equal to a quarter of a cycle always produces the number 0.25 regardless of the frequency of the waveforms. However, it's still considered a little clumsy.

The preferred method of quantifying phase difference involves expressing it as an angle by multiplying the simple ratio calculated above by 360°. Doing so for the examples in Figures 8a and 8b gives a phase difference of 90° ($0.25 \times 360° = 90°$).

The preferred method can be summarised mathematically as:

$$\boxed{\Phi \ difference = \frac{time\ diference}{period} \times 360^\circ}$$

Importantly, this equation can only be used when calculating the phase difference between two waveforms having the same frequency.

Practise calculating the phase difference between two signals for yourself by attempting the following questions.

1. What is the phase difference between the sinewaves in Figure 9?

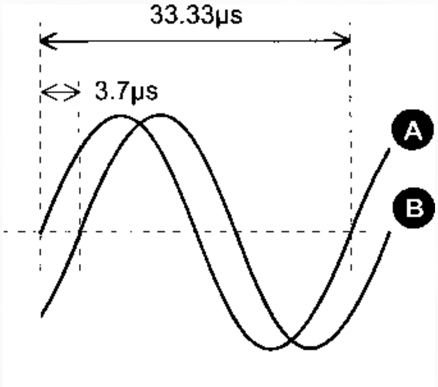


Figure 9

2. Which sinewave is leading?

3. What is the phase difference between the sinewaves in Figure 10?

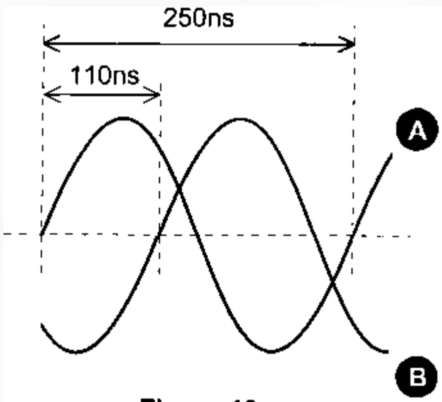


Figure 10

4. Which sinewave is leading?

It is usually more convenient to specify whether an AC waveform is leading or lagging another by using a plus ("+") or minus ("-") symbols. The plus symbol is used to denote a waveform is leading the reference and a minus symbol is used to denote a waveform is lagging the reference.

For example, if sinewave A in Figure 10 is the reference, sinewave B is -158.4° out of phase with it. Alternatively, if sinewave B is the reference then sinewave A is +158.4° out of phase.

Measuring phase difference

The phase difference between two waveforms is usually measured using an oscilloscope. The procedure for doing so is as follows:

1. Set the CRO's mode control to *Dual*.

2. Connect the CRO's channel 1 input to the reference waveform and its channel 2 input to the other waveform.

3. Adjust the CRO so that both waveforms are displayed (see Figure 11). Remember to make sure that all *CAL* controls are in their detent position!

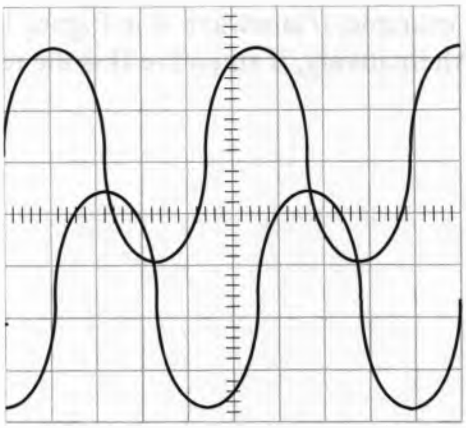


Figure 11

4. Set the *Input Coupling* control for both channels to the *GND* position so that the their traces are still displayed but the waveforms aren't (see Figure 12).

5. Adjust the *Vertical Position* controls of both channels so that the traces line up with the centre line on the graticule (see Figure 12).

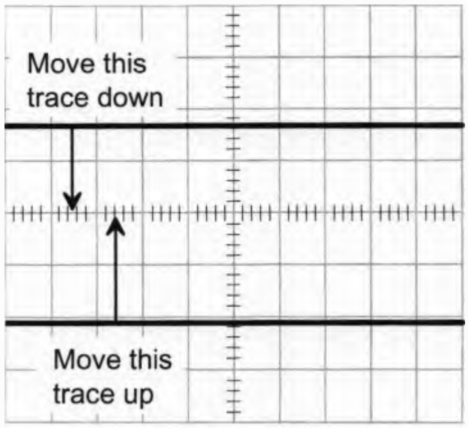


Figure 12

6. Set the *Input Coupling* control for one of the channels to the *AC* position so that one waveform is displayed (see Figure 13).

7. Count the number of divisions for one cycle of the waveform (you may adjust the *Horizontal Position* control to do this but **not** the *Vertical Position* control).

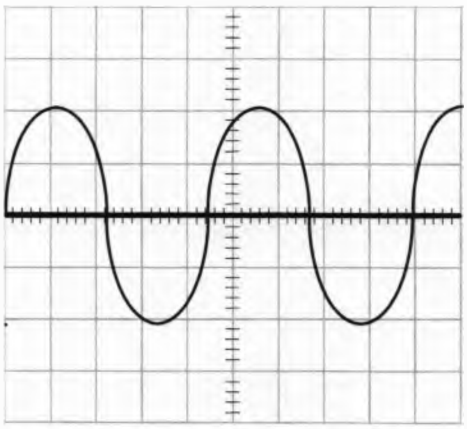


Figure 13

8. Set the *Input Coupling* control for the other channel to the *AC* position so that both waveforms are displayed again (see Figure 14).

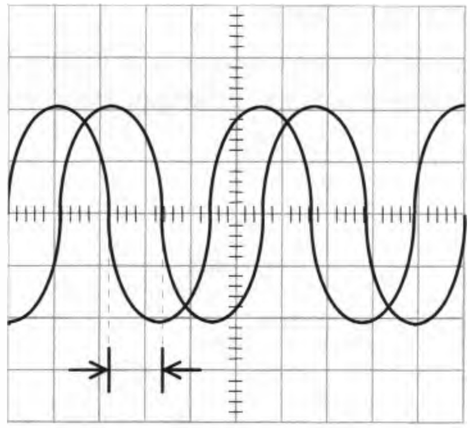


Figure 14

9. Count the number of divisions between the points where both waveforms cross the graticule's centre line (again, you can adjust the *Horizontal Position* control to do this but **not** the *Vertical Position* control).

10. Use the equation below to calculate the phase difference between the two waveforms in degrees.

$$\Phi\ difference = \frac{\text{Number of divisions between the two signals}}{\text{Number of divisions for the period of the input}} \times 360^{\circ}$$

11. Vary the channel 2 *Vertical Position* control to determine whether the waveform is leading or lagging the reference then add a "+" or a "-" in front of the phase difference accordingly.

You'll get an opportunity to practise this skill in the practical exercises of most of the remaining sections in this subject. Make sure that you can perform this activity because you will probably be asked to do this in the practical exam.

Phase inversion

Consider the two sinewaves in Figure 15 below. The calculations to the right of the diagram show that the phase difference between them is 180°.

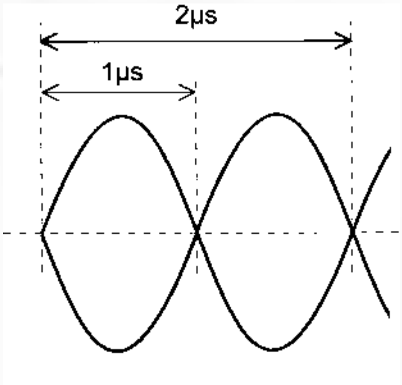


Figure 15

$$\Phi\ \textit{difference} = \frac{\textit{time diference}}{\textit{period}} \times 360^\circ$$

$$\Phi\ \textit{difference} = \frac{1\mu s}{2\mu s} \times 360^\circ$$

$$\Phi\ \textit{difference} = 180^\circ$$

The name that is often given to this amount of phase shift is called *phase inversion*. This is because one of the waveforms looks as though it has been turned upside-down.

But, has the waveform really been turned upside-down or has it been delayed by half a cycle? It's impossible to say for the waveforms in Figure 15 but consider the pairs of sinewaves in Figures 16a and 16b. One of the sinewaves in Figure 16a has literally been inverted but one of the sinewaves in Figure 16b has been delayed by half a cycle. Although both have a phase difference of 180°, the *pip* or *glitch* in the waveforms emphasises the difference.

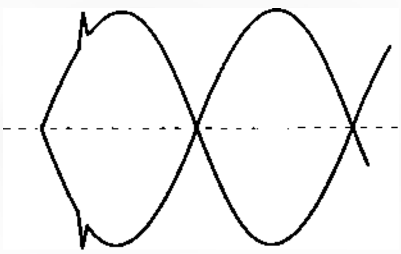


Figure 16a *One wave has been inverted*

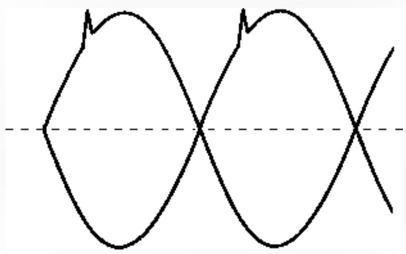


Figure 16b *One wave has been delayed*

You'll learn in later subjects whether or not it matters if a waveform is inverted or delayed by half a cycle.

Phasors

Drawing signals as they would appear on the display of a CRO is very useful because technicians use the CRO extensively for trouble-shooting faulty electronics equipment. However, this type of drawing can become very difficult to interpret when considering the phase relationship between three or more waveforms. This is especially true if their amplitudes are different. To demonstrate this point, consider Figure 17 below. As you can see, the drawing is a little busy.

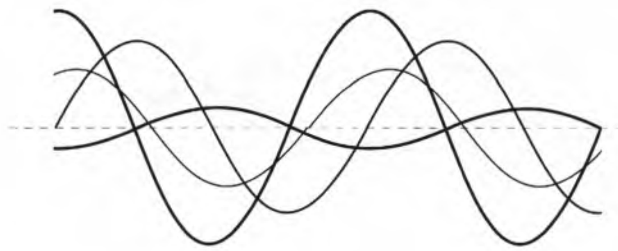


Figure 17 *Looking at more than a couple signals with different phase shifts can be confusing*

There's a different method of representing sinewaves that can be more useful when considering the phase relationship between so many waveforms. It's called the *phasor diagram* and, as the name implies, it uses *phasors*. A phasor is just a straight line that represents an individual sinewave. Figure 18 below shows a phasor representing a $12V_{pk}$ sinewave.

Figure 18 *The phasor representation of a single $12V_{pk}$ sinewave*

Importantly, although this can't be shown in Figure 18, phasors are said to rotate in an anti-clockwise direction as shown in Figure 19 below.

Figure 19 *Phasors rotate in an anti-clockwise direction*

Phasors are said to rotate anti-clockwise because their instantaneous angular position directly relates to the instantaneous voltage or current of the sinewave. This is illustrated in Figures 21 to 24.

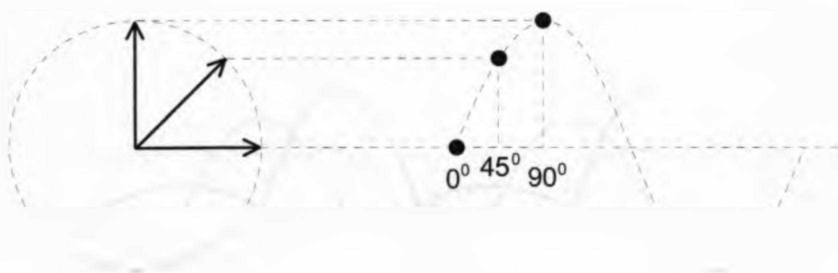


Figure 21 *A sinewave's phasor at 0°, 45° and 90° and its corresponding instantaneous voltages*

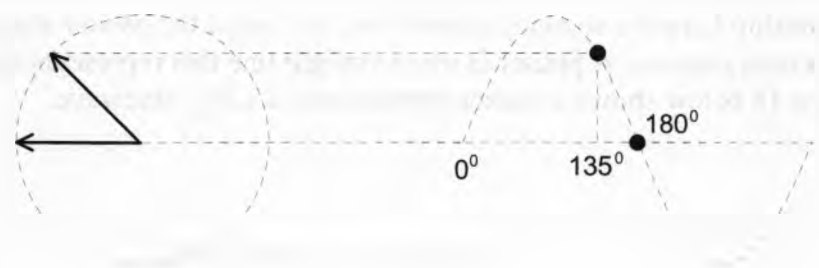


Figure 22 *A sinewave's phasor at 135° and 180° and its corresponding instantaneous voltages*

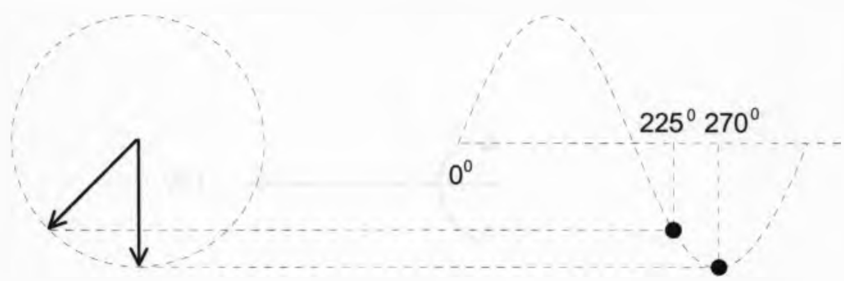


Figure 23 *A sinewave's phasor at 225° and 270° and its corresponding instantaneous voltages*

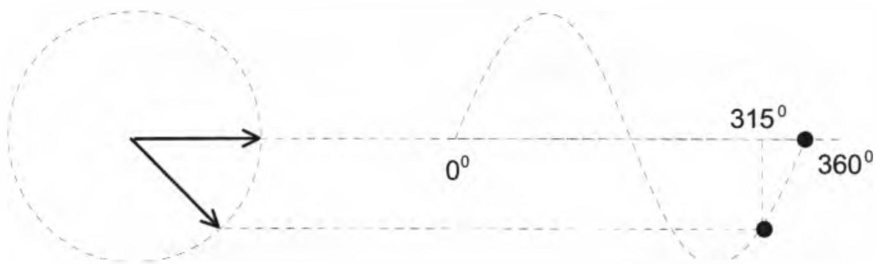


Figure 24 *A sinewave's phasor at 315° and 360° and its corresponding instantaneous voltages*

Rules for drawing phasors and phasor diagrams

There are a few rules that must be followed when drawing phasors and phasor diagrams:

- Phasors only represent sinewaves.
- Phasors always rotate anti-clockwise.
- The length of phasor must be proportional to the amplitude of the sinewaves they represent.

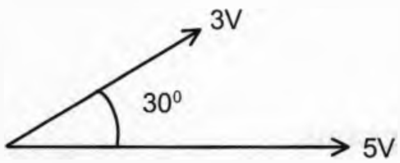
  So, if there are two sinewaves with one twice the amplitude of the other, the phasor representing the bigger sinewave must be twice as long as the other.
- A phasor's length always represents the sinewave's **peak** value.

  As this is widely understood, the "pk" that must normally be written next to the voltage to denote this fact is left off.
- Phasors must be drawn to scale (though, we break this rule in this subject as relative scale will do).
- The arrow head of voltage phasors are open-ended and for current phasors they're closed-ended.
- When a phasor diagram consists of more than one sinewave, the phasor for the reference sinewave is shown as being at 0°.

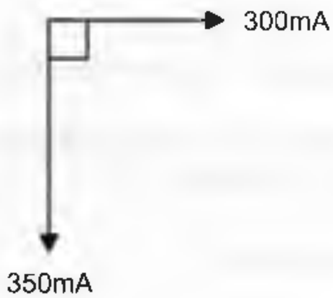
Some examples of phasor diagrams are shown in Figure 25 below with a description of each.

A $50V_{pk}$ sinewave.

A $2A_{pk}$ sinewave.

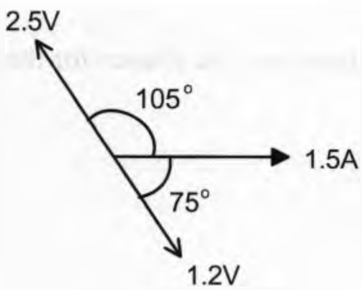


A $5V_{pk}$ reference sinewave with a $3V_{pk}$ sinewave leading it by 30°.



A $300mA_{pk}$ reference sinewave with a $350mA_{pk}$ sinewave lagging it by 90°.

A $38mA_{pk}$ sinewave in phase with an $85mV_{pk}$ sinewave.



A $1.5A_{pk}$ reference sinewave with a $2.5V_{pk}$ sinewave leading it by 105° and a $1.2V_{pk}$ sinewave lagging it by 75°.

Figure 25

Student notes

Skill practice 4

Practise measuring voltage of, and the phase difference between, signals using an oscilloscope

This exercise is practise for the sorts of skills you may be required to perform in a practical test. Remember, in any practical tests you will be working alone so make sure that you can perform all the steps. It should take you about 1½ hours to complete this exercise.

Equipment

- Filter module
- three BNC-BNC leads
- BNC to alligator-clip lead

Remember:

Follow TAFE NSW WHS guidance at all times!

Work tasks

1. Read your WHS responsibilities at the top of the form below. Then conduct a WHS risk assessment and record your findings in the space provided.

Responsibilities of students under the Model WHS Act: s28

- Take reasonable care for your own health and safety by working safely at all times
- Take reasonable care to ensure that your acts or omissions don't put the health and safety of others at risk
- Follow all TAFE NSW WHS guidance and comply with all reasonable instructions from TAFE NSW staff to assist them in complying with the TAFE NSW WHS requirements
- In addition to the above, you must:
  - use and maintain machinery, tools and all other equipment properly and safely
  - ensure that your work area is free of hazards
  - notify a TAFE NSW staff member of actual or potential hazards
  - wear/use prescribed safety equipment
  - take notice of any safety signs and adhere to their instructions

Risks involved in this activity include:	**Control measures:**
Trip hazards (eg students bags) Objects dropped on feet (while equipment is taken to and from workbenches). Others: ____________________ ____________________ ____________________	Move bags and other objects from walkways Plan lifting of equipment Other: ____________________ ____________________ ____________________

My signature here indicates that I have read and understand my responsibilities under the Model WHS Act s28 (detailed above). I have also conducted a risk assessment before undertaking this activity and have identified measures to control these risks and have implemented them.

Signature: ____________________ Date: ____________

Part A - Learning to operate the function generator

2. Gather the equipment needed for this exercise.

3. Set up the CRO per the procedure on pages 3-6 and 3-7.

4. Turn on the bench-mounted function generator and set it up as follows:

   (a) Press the appropriate *Function* button for a sinewave output (see Figure 1 below).

   (b) Rotate the *Amplitude Adjust* control fully clockwise.

   (c) Press the 1k *Frequency Range* button.

   (d) Rotate the *Frequency Adjust* control to about half its travel.

   (e) Ensure that the *-20dB Attenuation* control is deactivated. (Note: This control is in different positions on different generators so if you can't find it, call the teacher.)

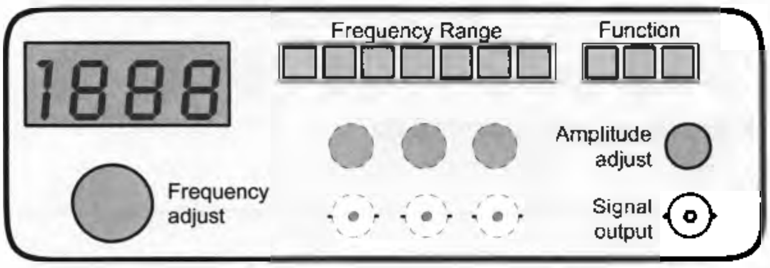


Figure 1

5. Use a BNC to BNC lead to connect the function generator's output to the CRO's channel 1 input.

6. Press the other two *Function* buttons and note what happens to the function generator's output signal.

Question 1
What is the purpose of the *Function* control?

7. Set the function generator to give a sinewave output.

8. Measure the peak-to-peak voltage of the waveform and record your measurement in Table 1 below.

9. Rotate the *Amplitude* control fully anti-clockwise.

10. Measure and record the new output voltage. (**Note:** You'll need to adjust the CRO's vertical attenuation control to do this.)

11. Activate the *-20dB Attenuation* control.

12. Rotate the *Amplitude* control fully clockwise and repeat steps 7 to 9.

Table 1	**Amplitude knob fully clockwise**	**Amplitude knob fully anti-clockwise**
Without attenuation		
With attenuation		

Question 2
What does the *Amplitude Adjust* control do?

Question 3
What does the *-20dB Attenuation* control do?

---

13. Rotate the *Amplitude* control fully clockwise.

14. Rotate the *Frequency Adjust* control so that its in the middle of its travel.

15. Measure the period of the output signal using the oscilloscope. (**Note:** You'll need to adjust the CRO's horizontal sweep controls to do this.)

16. Record your measurement in the first row and column in Table 2 on the next page.

17. Use this information and the equation $f = \frac{1}{P}$ to calculate and record the frequency of the output signal.

18. Rotate the *Frequency Adjust* control fully clockwise.

19. Measure and record the period of the output signal.

20. Use this information to calculate and record the new frequency of the output signal.

21. Repeat steps 13 to 19 for the function generator's *10kHz* and *100kHz* ranges.

Table 2

Range	Period of signal (Step 15)	Its frequency (Step 17)	Period of signal (Step 19)	Its frequency (Step 20)
1kHz				
10kHz				
100kHz				

Question 4
What's the difference between of the *Frequency Adjust* and *Range* controls?

____

____

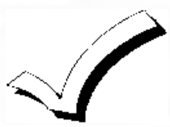
____

Question 5
What happens to the **period** of the output signal as you rotate the *Frequency Adjust* control anti-clockwise? If you're not sure, check your results in Table 2.

____

Question 6
What happens to the **frequency** of the output signal as you rotate the *Frequency Adjust* control anti-clockwise?

____



The teacher needs to check your work at this point...

Figure 2a below shows an RL circuit and Figure 2b shows an equivalent circuit where the total resistive effect of the resistor and the inductor is represented by the impedance (Z).

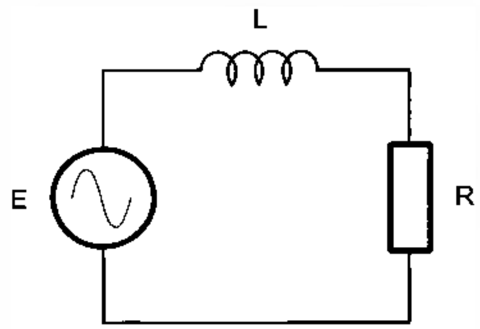


Figure 2a *An RL circuit*

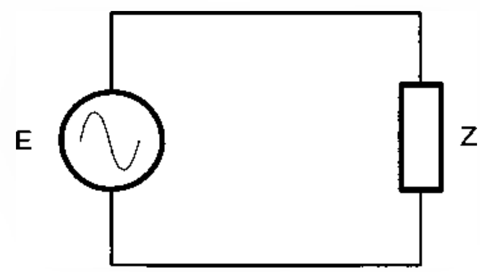


Figure 2b *The single impedance equivalent circuit of Figure 2a*

Figure 2b is also an equivalent circuit for RC and RLC circuits.

Calculating the impedance of RL circuits

The key to understanding how to calculate the impedance of RL circuits is to represent the resistance and reactance in a special kind of *vector diagram* called an *impedance triangle*. A vector diagram is similar to a phasor diagram except the lines aren't rotating. To demonstrate, let's develop the impedance triangle for the circuit in Figure 3 below.

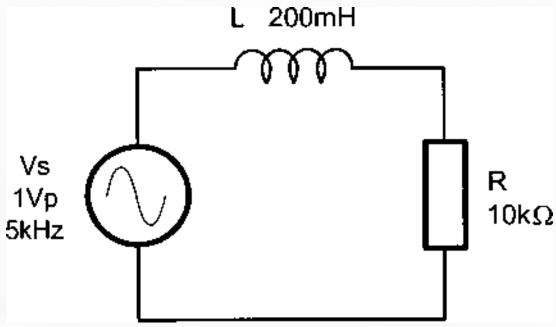


Figure 3 *An RL circuit*

As you can see, the resistor's value is 10kΩ and a quick calculation (using $X_L = 2\pi fL$) gives the inductor's reactance as 6283Ω. So the vector diagram showing the resistance and inductive reactance in the circuit looks like Figure 4 below.

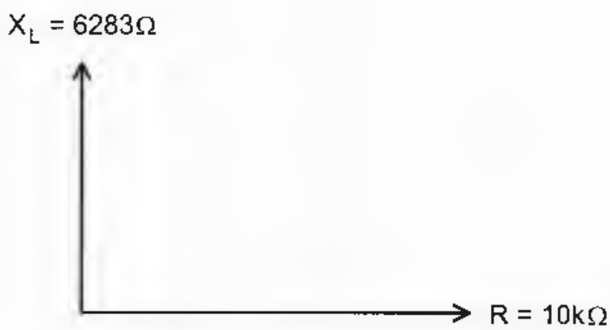


Figure 4 *The vector diagram showing the resistance and inductive reactance in the circuit in Figure 3*

Notice that the vectors in the diagram above are at right angles. It's difficult to explain why the vector for inductive reactance should point up without using some heavy-duty maths. However, think of it this way. The inductor's effect on the circuit current can be described in terms of the inductor's reactance and the potential difference across it (because $I = \frac{V_L}{X_L}$). And as you know, the potential difference across the inductor leads the circuit current by 90° so the inductor's reactance must be shown in the same direction.

The circuit impedance can be found using the vector diagram in Figure 4 by drawing lines perpendicular to the ends of the vectors for inductive reactance and resistance. The point where the lines cross marks the end of the impedance vector and this is shown in Figure 5 below.

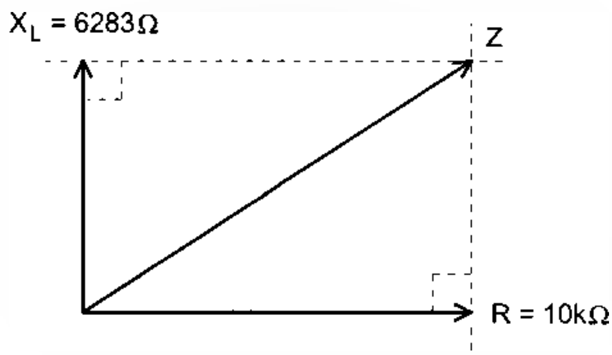


Figure 5 *The impedance can be found by drawing perpendicular lines from the ends of the vectors for inductive reactance and resistance*

If the vector for inductive reactance is moved so that it starts from the end of the vector for resistance and all of the arrow heads are chopped off, the diagram above looks like Figure 6. From this it can be seen why the vector diagram above is often referred to as an *impedance triangle*.

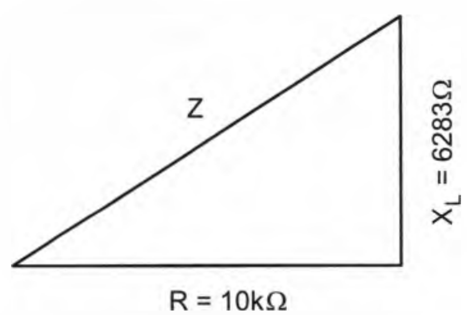


Figure 6 *Redrawn this way, it is easy to see why Figure 5 is called an impedance triangle*

Figure 6 clearly shows that the resistance and the inductive reactance form two sides of a right-angled triangle and the circuit impedance forms the hypotenuse. That being the case, if the resistance and inductive reactance are known the impedance can be calculated using the equation:

$$\boxed{Z = \sqrt{R^2 + X_L^2}}$$

So, the impedance of the circuit in Figure 3 is:

$$Z = \sqrt{R^2 + X_L^2}$$

$$Z = \sqrt{10k\Omega^2 + 6283^2}$$

$$Z = 11,810\Omega$$

Practise calculating the impedance of RL circuits by trying the following questions.

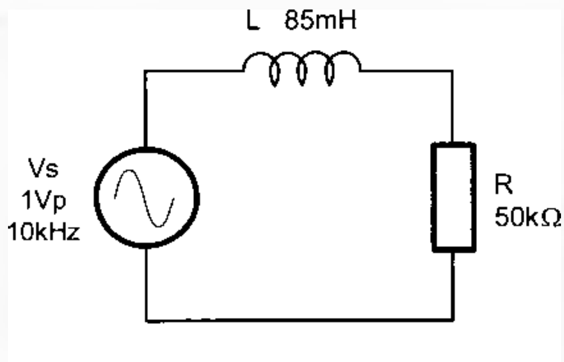


Figure 7

1. Calculate the reactance of the inductor in the circuit of Figure 7.

2. Calculate the circuit's impedance.

3. Draw the impedance triangle showing resistance, inductive reactance and impedance.

4. Calculate the inductor's reactance if the EMF's frequency is increased to 80kHz.

5. Calculate the new impedance.

6. Draw the new impedance triangle showing resistance, inductive reactance and impedance.

7. Calculate the inductor's reactance if the EMF's frequency is increased to 500kHz.

8. Calculate the new impedance.

9. Draw the new impedance triangle showing resistance, inductive reactance and impedance.

Calculating the impedance of RC circuits

The process for calculating the impedance of RC circuits is the same as for RL circuits but, in terms of drawing the impedance triangle, there is important difference between RL and RC circuits. To explain, let's develop the impedance triangle for the circuit in Figure 8 below.

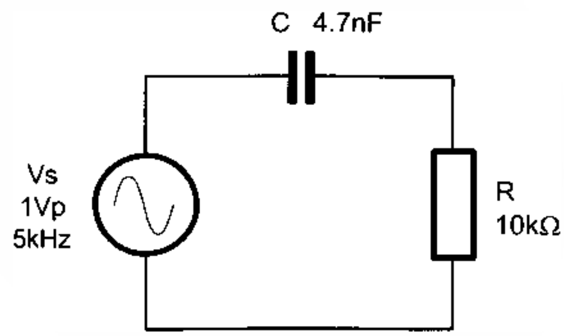


Figure 8 *An RC circuit*

As you can see, the resistor's value is 10kΩ and a quick calculation (using $X_C = \frac{1}{2\pi fC}$) gives the capacitor's reactance as 6773Ω. So the vector diagram showing the resistance and capacitive reactance in the circuit looks like Figure 9 below.

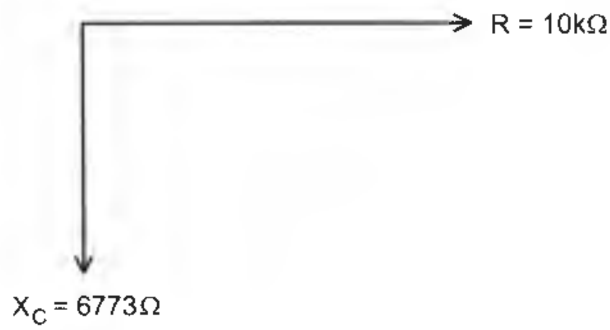


Figure 9 *The vector diagram showing the resistance and inductive reactance in the circuit of Figure 8*

Notice that the vectors in the diagram above are at right angles. Again, it's difficult to explain why the vector for capacitive reactance should point down without using some heavy-duty maths. However, think of it this way. The capacitor's effect on the circuit current can be described in terms of the capacitor's reactance and the potential difference across it (because $I = \frac{V_C}{X_C}$). And as you know, the potential difference across the capacitor lags the circuit current by 90° so the capacitor's reactance must be shown in the same direction. This is the important difference between RL and RC circuits. In RL circuits the inductive reactance points up and in RC circuits the capacitive reactance points down.

The circuit impedance can be found using the vector diagram in Figure 9 by drawing lines perpendicular to the ends of the vectors for capacitive reactance and resistance. The point where the lines cross marks the end of the impedance vector and this is shown in Figure 10 below.

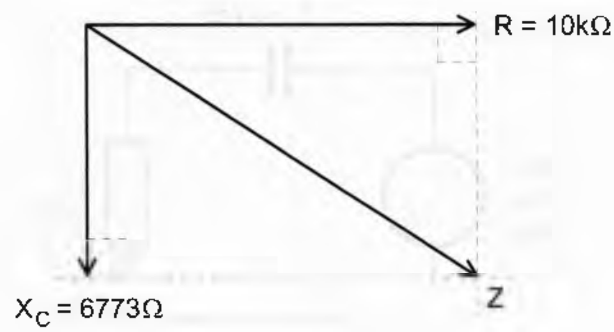


Figure 10 *The impedance can be found by drawing perpendicular lines from the ends of the vectors for capacitive reactance and resistance*

Figure 10 clearly shows that the resistance and the capacitive reactance form two sides of a right-angled triangle and the circuit impedance forms the hypotenuse. That being the case, if the resistance and capacitive reactance are known the impedance can be calculated using the equation:

$$\boxed{Z = \sqrt{R^2 + X_C^2}}$$

So, the impedance of the circuit in Figure 8 is:

$$Z = \sqrt{R^2 + X_C^2}$$

$$Z = \sqrt{10k\Omega^2 + 6773\Omega^2}$$

$$Z = 12{,}078\Omega$$

Practise calculating the impedance of RC circuits by trying the following questions.

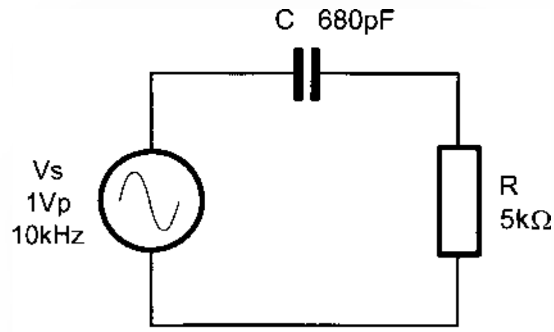


Figure 11

1. Calculate the reactance of the capacitor in the circuit of Figure 11.

2. Calculate the circuit's impedance.

3. Draw the impedance triangle showing resistance, capacitive reactance and impedance.

4. Calculate the capacitor's reactance if the EMF's frequency is increased to 100kHz.

5. Calculate the new impedance.

6. Draw the new impedance triangle showing resistance, capacitive reactance and impedance.

7. Calculate the capacitor's reactance if the EMF's frequency is increased to 500kHz.

8. Calculate the new impedance.

9. Draw the new impedance triangle showing resistance, capacitive reactance and impedance.

Calculating the impedance of RLC circuits

As we have seen, the vectors for inductive and capacitive reactance point in opposite directions in impedance triangles. This suggests that they oppose each others' action and, in terms of their effect on impedance, this is true. So, in RLC circuits the net reactance in the circuit must be found before impedance can be calculated and drawn. To demonstrate this point, consider the circuit in Figure 12 below.

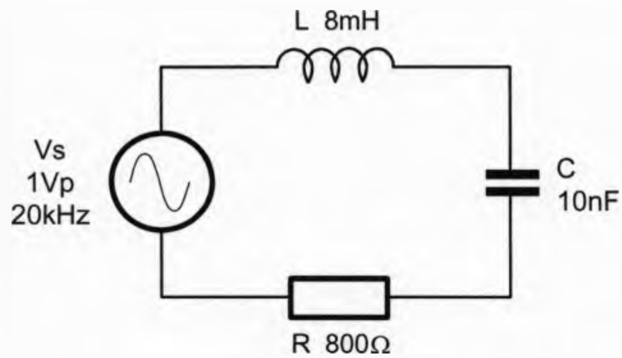


Figure 12 *An RLC circuit*

As you can see, the resistor's value is 800Ω and a couple of quick calculation gives the inductor's reactance as 1005Ω and the capacitor's reactance as 796Ω. So the vector diagram showing the resistance and reactances in the circuit looks like Figure 13 below.

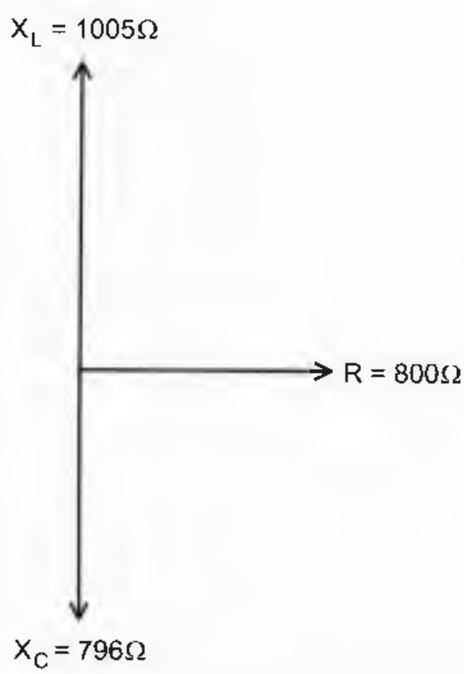


Figure 13 *The vector diagram showing the resistance and reactances in the circuit in Figure 12*

The circuit impedance can be found using the vector diagram in Figure 13 by drawing a line perpendicular to the end of the vector for resistance and a line perpendicular to the difference between the vectors for inductive and capacitive reactance. The point where the lines cross marks the end of the impedance vector and this is shown in Figure 14 below.

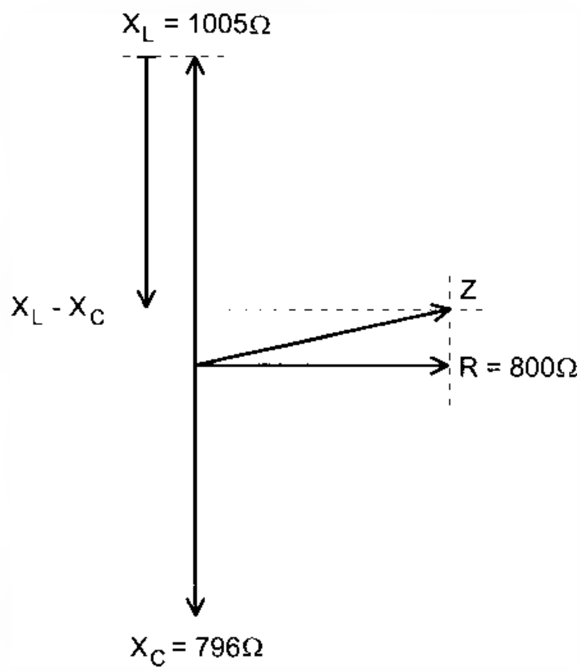


Figure 14 *The impedance can be found by drawing a perpendicular line from the end of the vectors for resistance and another line perpendicular to the difference between the vectors for inductive and capacitive reactance.*

Figure 14 clearly shows that the resistance and the difference between inductive and capacitive reactance form two sides of a right-angled triangle and the circuit impedance forms the hypotenuse. That being the case, if the resistance and capacitive reactance are known the impedance can be calculated using the equation:

$$\boxed{Z = \sqrt{R^2 + (X_L - X_C)^2}}$$

So, the impedance of the circuit in Figure 12 is:

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$$Z = \sqrt{800\Omega^2 + (1005 - 796)^2}$$

$$Z = \sqrt{640,000 + 43,681}$$

$$Z = 827\Omega$$

Practise calculating the impedance of RLC circuits by trying the following questions.

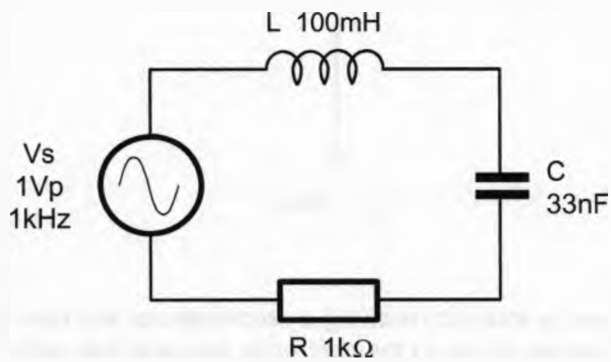


Figure 15

1. Calculate the inductor's reactance in the circuit of Figure 15.

____

____

2. Calculate the capacitor's reactance.

____

____

3. Calculate the circuit's impedance.

4. Draw the impedance triangle showing resistance, the reactances and impedance.

5. Calculate the inductor's reactance if the EMF's frequency is increased to 5kHz.

6. Calculate the capacitor's new reactance.

7. Calculate the new impedance.

8. Draw the new impedance triangle showing resistance, the reactances and impedance.

9. Calculate the inductor's reactance if the EMF's frequency is changed to 2771Hz.

10. Calculate the capacitor's new reactance.

11. Calculate the new impedance.

12. Draw the new impedance triangle showing resistance, the reactances and impedance.

Student notes

Skill practice 8

Practise measuring AC voltages in series RL, RC and RLC circuits using an oscilloscope

This exercise is practise for the sorts of skills you may be required to perform in a practical test. Remember, in any practical tests you will be working alone so make sure that you can perform all the steps. It should take you about 1½ hours to complete this exercise.

Equipment

- Interface panel
- 2.5mH inductor
- 1nF capacitor
- 1kΩ ½W resistor
- two BNC to banana-plug leads
- banana leads

Remember:

Follow TAFE NSW WHS guidance at all times!

Work tasks

1. Read your WHS responsibilities at the top of the form below. Then conduct a WHS risk assessment and record your findings in the space provided.

<table>
<tr><td colspan="2">

Responsibilities of students under the Model WHS Act: s28

- Take reasonable care for your own health and safety by working safely at all times
- Take reasonable care to ensure that your acts or omissions don't put the health and safety of others at risk
- Follow all TAFE NSW WHS guidance and comply with all reasonable instructions from TAFE NSW staff to assist them in complying with the TAFE NSW WHS requirements
- In addition to the above, you must:
  - use and maintain machinery, tools and all other equipment properly and safely
  - ensure that your work area is free of hazards
  - notify a TAFE NSW staff member of actual or potential hazards
  - wear/use prescribed safety equipment
  - take notice of any safety signs and adhere to their instructions

</td></tr>
<tr><td>

Risks involved in this activity include:

Trip hazards (eg students bags)
Objects dropped on feet (while equipment is taken to and from workbenches).

Others: ____________________

____

____

</td><td>

Control measures:

Move bags and other objects from walkways
Plan lifting of equipment

Other: ____________________

____

____

</td></tr>
<tr><td colspan="2">

My signature here indicates that I have read and understand my responsibilities under the Model WHS Act s28 (detailed above). I have also conducted a risk assessment before undertaking this activity and have identified measures to control these risks and have implemented them.

Signature: ____________________ Date: ____________________

</td></tr>
</table>

2. Gather the equipment needed for this exercise.

3. Wire the circuit of Figure 1 on the interface panel.

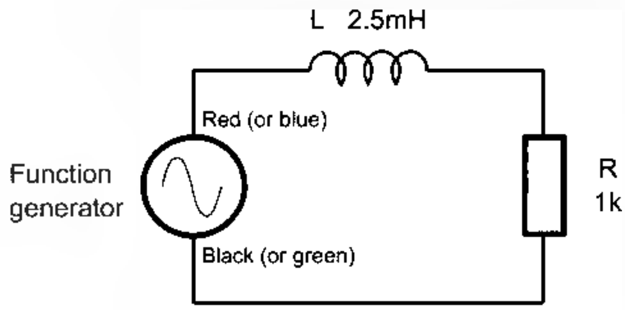


Figure 1

4. Set the function generator's output for a 10kHz sinewave.

5. Set the amplitude of function generator's output to maximum.

6. Measure and record the function generator's peak-to-peak output voltage using the CRO. Be as accurate as possible with your measurement.

   Note: The output voltage should be at about 20V. If it's much smaller than this you may need to turn off the -20dB attenuator function.

   $V_S =$ ______________________________

7. Accurately measure the peak-to-peak potential difference across the resistor (V_R) using the CRO. Record your measurement in Table 1 (on the next page).

8. Calculate and record the peak-to-peak circuit current (I) using this measurement and the equation: $I = \frac{V_R}{R}$.

The teacher needs to check your work at this point...

9. Repeat steps 7 and 8 for each of the frequencies listed in Table 1.

Table 1

Frequency	V_R (Step 7)	**Circuit current (I)** (Step 8)
10kHz		
50kHz		
100kHz		
200kHz		

Question 1
Compare the *Frequency* and *Circuit current* columns. What happens to the circuit current as the function generator's output frequency increases?

____

Question 2
What is the chain of events that is causing the current to change as frequency increases?

____

____

____


The teacher needs to check your work at this point...

10. Wire the circuit of Figure 2.

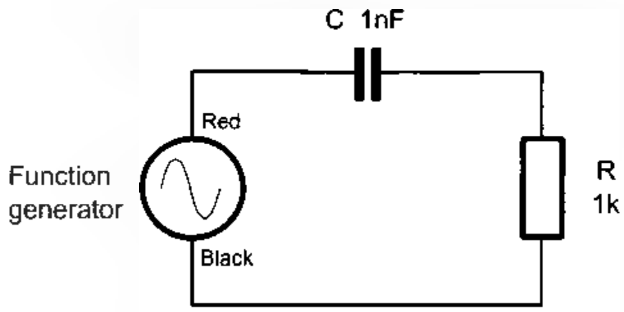


Figure 2

11. Set the function generator's output for a 500kHz sinewave.

12. Set the amplitude of function generator's output to maximum.

13. Accurately measure and record the function generator's output voltage using the CRO.

$V_S =$ ______________________________

14. Accurately measure the peak-to-peak potential difference across the resistor (V_R) using the CRO. Record your measurement in Table 2 (below).

15. Calculate and record the peak-to-peak circuit current (I) using this measurement and the equation: $I = \frac{V_R}{R}$.

The teacher needs to check your work at this point...

16. Repeat steps 14 and 15 for each of the frequencies listed in Table 2.

Table 2

Frequency	V_R	Circuit current (I)
20kHz		
50kHz		
100kHz		
500kHz		

Question 3
Compare the *Frequency* and *Circuit current* columns. What happens to the circuit current as the function generator's output frequency increases?

Question 4
What is the chain of events that is causing the current to change as frequency increases?

Question 5
What's the difference between inductive and capacitive reactance in the way they affect circuit impedance?

The teacher needs to check your work at this point...

17. Wire the circuit of Figure 3.

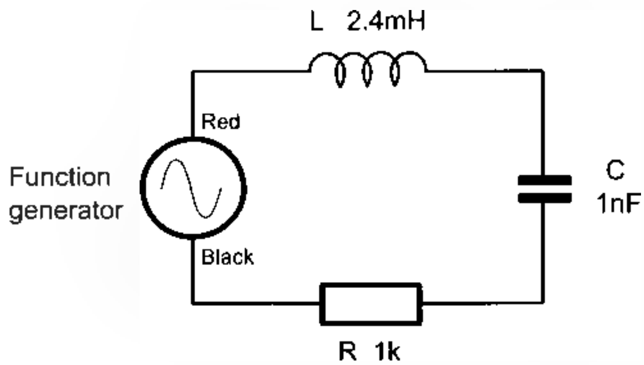


Figure 3

18. Set the function generator's output for a 20kHz sinewave.

19. Set the amplitude of function generator's output to maximum.

20. Accurately measure and record the function generator's output voltage using the CRO.

V_S = ______________________

21. Accurately measure the peak-to-peak potential difference across the resistor (V_R) using the CRO. Record your measurement in Table 3 (on the next page).

22. Calculate and record the peak-to-peak circuit current (I).

The teacher needs to check your work at this point...

23. Repeat steps 21 and 22 for each of the frequencies listed in Table 3.

24. For the blank cell in the frequency column, set the function generator to the frequency that gives the biggest voltage across the resistor (which should be around 100kHz). Record the frequency.

25. Repeat steps 21 and 22 for that frequency.

Table 3

	Frequency	V_R	Circuit current (I)
	20kHz		
	50kHz		
	75kHz		
See Step 24 ▶			
	125kHz		
	175kHz		
	300kHz		

Question 6
Compare the *Frequency* and *Circuit current* columns. What happens to the circuit current as the function generator's output frequency increases?

____

____

Question 7
What is the chain of events that is causing the current to change as frequency increases?

____

____

____

Question 8
Which component has the most effect on the circuit current at low frequencies? Explain your answer.

Question 9
Which component has the most effect on the circuit current at high frequencies? Explain your answer.

Question 10
Which component has the most effect on the circuit current at the frequency where the output voltage is maximum ? Explain your answer.

The teacher needs to check your work at this point...

Student notes

Review questions

Answer these questions to check your understanding of what you have learnt for this chapter. Doing this will also help to prepare you for the tests.

1. What is impedance?

____

____

2. Impedance is measured in

- ☐ Ohms.
- ☐ Reactohms.
- ☐ Impedohms.
- ☐ Zedohms.

Questions 3 to 6 refer to the circuit of Figure 1

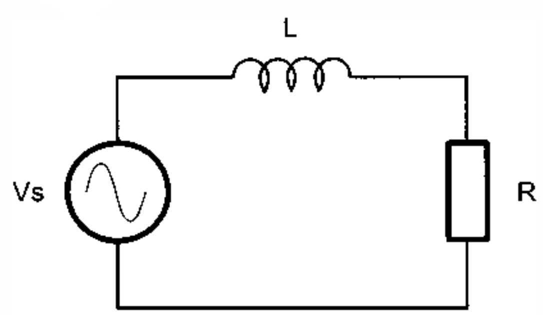


Figure 1

3. What would happen to the circuit impedance if the frequency of V_S increased?

- ☐ Decrease
- ☐ Remain the same
- ☐ Increase
- ☐ Increase until V_S reached the resonant frequency then decrease

4. What would happen to the circuit current if the frequency of V_S increased?

- ☐ Decrease
- ☐ Remain the same
- ☐ Increase
- ☐ Increase until V_S reached the resonant frequency then decrease

5. What would happen to the circuit impedance if the amplitude of V_S increased?

- ☐ Decrease
- ☐ Remain the same
- ☐ Increase
- ☐ Increase until V_S reached the resonant frequency then decrease

6. When would the circuit impedance seem mostly resistive?

- ☐ When V_S is a relatively low frequency
- ☐ At the resonant frequency
- ☐ When V_S is a relatively high frequency
- ☐ At the anti-resonant frequency

Questions 7 to 10 refer to the circuit of Figure 2

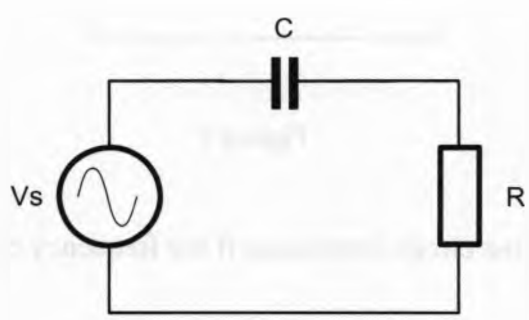


Figure 2

7. What would happen to the circuit impedance if the frequency of V_S increased?

- ☐ Decrease
- ☐ Remain the same
- ☐ Increase
- ☐ Increase until V_S reached the resonant frequency then decrease

8. What would happen to the circuit current if the frequency of V_S increased?

- ☐ Decrease
- ☐ Remain the same
- ☐ Increase
- ☐ Increase until V_S reached the resonant frequency then decrease

9. What would happen to the circuit impedance if the amplitude of V_S increased?

- ☐ Decrease
- ☐ Remain the same
- ☐ Increase
- ☐ Increase until V_S reached the resonant frequency then decrease

10. When would the circuit impedance seem mostly resistive?

- ☐ When V_S is a relatively low frequency
- ☐ At the resonant frequency
- ☐ When V_S is a relatively high frequency
- ☐ At the anti-resonant frequency

Questions 11 to 13 refer to the circuit of Figure 3

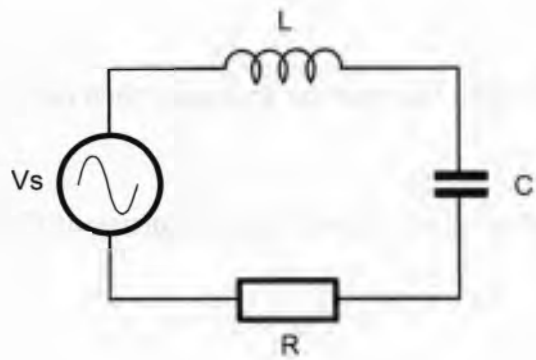


Figure 3

11. What would happen to the circuit impedance if the frequency of V_S increased from a very low to a very high frequency?

- ☐ Decrease
- ☐ Decrease until V_S reached the resonant frequency then increase
- ☐ Increase
- ☐ Increase until V_S reached the resonant frequency then decrease

12. What would happen to the circuit current if the frequency of V_S increased from a very low to a very high frequency?

- ☐ Decrease
- ☐ Decrease until V_S reached the resonant frequency then increase
- ☐ Increase
- ☐ Increase until V_S reached the resonant frequency then decrease

13. When would the circuit impedance seem totally resistive?

- ☐ When V_S is a relatively low frequency
- ☐ At the resonant frequency
- ☐ When V_S is a relatively high frequency
- ☐ At the anti-resonant frequency

14. For the circuit of Figure 4, calculate:

    (a) the inductor's reactance

    (b) the circuit impedance

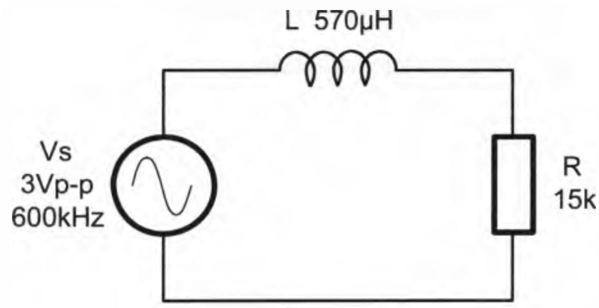


Figure 4

15. Draw the impedance triangle for the circuit of Figure 4 at the frequency given.

16. For the circuit of Figure 5, calculate:

    (a) the capacitor's reactance

    (b) the circuit impedance

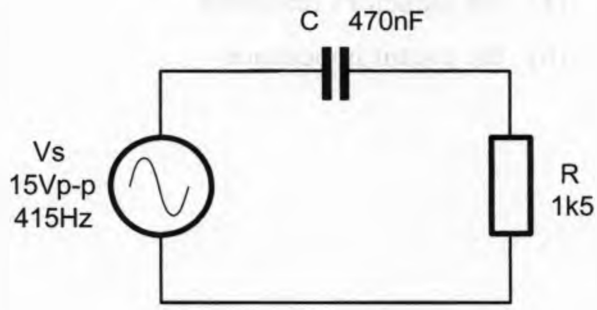


Figure 5

17. Draw the impedance triangle for the circuit of Figure 5 at the frequency given.

18. For the circuit of Figure 6, calculate:

    (a) the inductor's reactance

    (b) the capacitor's reactance

    (c) the circuit impedance

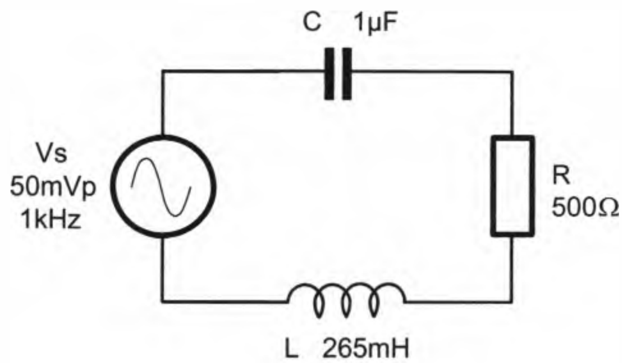


Figure 6

19. Draw the impedance triangle for the circuit of Figure 6 at the frequency given.

Student notes

Section 9 Calculating voltages and currents around RL, RC and RLC circuits

Purpose To develop your skills so that you can test simple AC circuits made from resistors & inductors, resistor & capacitors and resistors, inductors and capacitors connected in series.

Objectives At the end of this section you should be able to:

- Calculate either the current, voltage or impedance of a series RL or RC circuit given a value for the other two (where the voltage and current can be specified using either peak, peak-to-peak, RMS or instantaneous values)
- Calculate potential differences across components of known value in series RL or RC circuits given either the supply voltage or circuit current (where the voltages and currents can be specified using either peak, peak-to-peak, RMS or instantaneous values)
- Describe the *resonance* effect in terms of the impedance in series RLC circuits
- State the relationship between inductive and capacitive reactance at resonance in series RLC circuits
- Measure potential difference in AC circuits using an oscilloscope and use this to confirm predicted values

Introduction

The last two sections have discussed the operation of series RL, RC and RLC circuits, how to calculate the reactance of inductors and capacitors and how to calculate the total circuit impedance. This section takes the analysis of these circuits one step further by showing you how to calculate the circuit current and the potential differences across the components.

A brief but important revision of series resistive circuits

Before you get into the maths involved in analysing RL, RC and RLC circuits, an important point to make here is that calculating the circuit current and the potential differences across the components in these circuits involves a procedure that you already know. It is the one that you use to calculate the current and voltages in a series resistive circuit.

Let's revise that procedure by analysing the series resistive circuit in Figure 1.

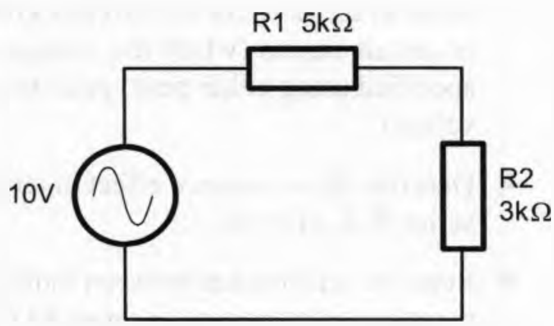


Figure 1 *A simple series resistive circuit*

To find the circuit current and the potential difference across resistors *R1* and *R2* you must do the following:

1. Find the total circuit resistance (R_T).

   This is found using the equation: $R_T = R1 + R2$. In this example R_T is 8kΩ.

2. Find the circuit current (I).

   This is found using Ohm's Law: $I = \frac{E}{R_T}$. In this example I is 1.25mA.

3. Find the potential difference across *R1*.

   This is found using Ohm's Law: $V_{R1} = I \times R1$. In this example V_{R1} is 6.25V.

4. Find the potential difference across *R2*.

   This is found using Ohm's Law: $V_{R2} = I \times R2$. In this example V_{R2} is 3.75V.

Finally, your answers can be checked by simply adding the potential differences across the resistors to see if they equal the supply voltage. If they do then there is a good chance that all of your calculations are correct. In this example, 6.25V plus 3.75V equals 10V so the calculations look good.

The procedure for finding the circuit current and voltages around RL, RC and RLC circuits is basically the same but there are two differences. First, because the circuits contain one or more reactive components, their reactance at the frequency of the supply must be calculated and this must be done first. Second, because voltages and currents around these circuits are out of phase with each other, simple addition cannot be used to find any totals.

Analysing RC circuits

Let's analyse the RC circuit in Figure 2 below by calculating the current and potential difference across the capacitor and resistor.

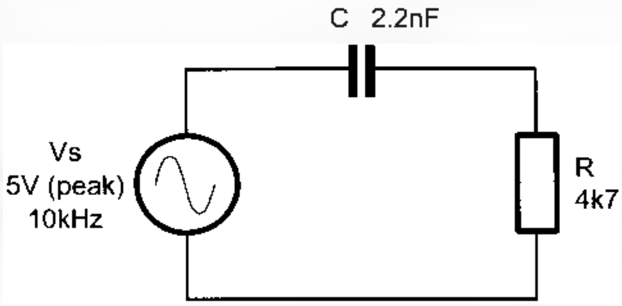


Figure 2 *A series RC circuit*

Procedure:

1. Find the reactance of the capacitor (X_C).

   This is found using the equation: $X_C = \frac{1}{2\pi fC}$. In this example X_C is 7.23kΩ.

2. Find the total circuit impedance (Z).

   This is found using the equation: $Z = \sqrt{R^2 + X_C^2}$. In this example Z is 8.63kΩ.

3. Find the circuit current (I).

   This is found using Ohm's Law: $I = \frac{E}{Z}$. In this example I is 579.6μA (peak).

4. Find the potential difference across the resistor (V_R).

   This is found using Ohm's Law: $V_R = I \times R$. In this example V_R is 2.72V (peak).

5. Find the potential difference across the capacitor (V_C).

   This is found using Ohm's Law: $V_C = I \times X_C$. In this example V_C is 4.19V (peak).

Figure 3 below shows the current and potential differences that have just been calculated as phasors in a phasor diagram. As the circuit is a series circuit, current is the reference.

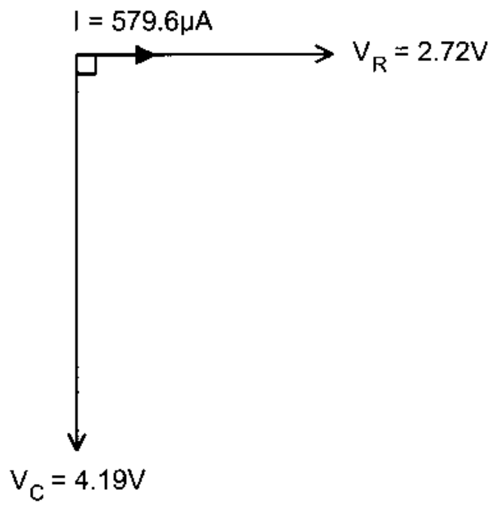


Figure 3 *The phasor diagram showing current and voltages around the circuit of Figure 2*

At this point, if we were analysing a series resistive circuit we could check these calculations by simply adding the potential differences across the two components and if they added up to the supply voltage then we could be reasonably confident that they are correct. However, if we do this for the circuit of Figure 2 we find that 2.72V plus 4.19V adds up to more than 5V!

So, have we done something wrong? No. The test hasn't worked for this circuit because the potential differences around the circuit including the supply voltage (V_S) are all out of phase with each other. On a phasor diagram, the phasor for V_S sits between the phasors of the other two voltages as shown in Figure 4 below.

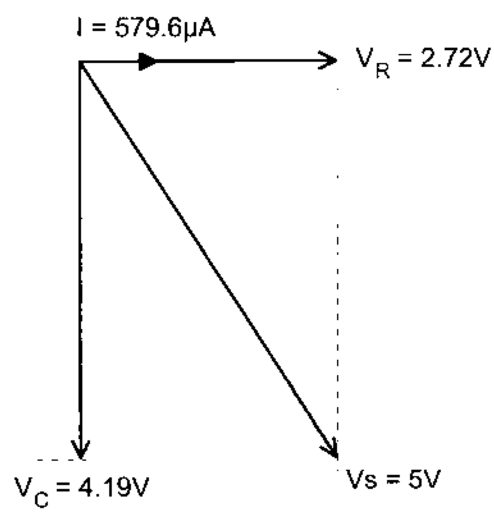


Figure 4 *The phasor for V_S sits between the phasors for V_R and V_C*

From this diagram it can be seen that the supply voltage does not equal the simple addition of V_R and V_C. However, as the phasor for the supply voltage forms the hypotenuse of a right-angled triangle with the phasors for V_R and V_C whose values are known, then V_S can be found by adapting Pythagoras' Theorem in the same way that it is for impedance triangles. So, the supply voltage can be found using the equation:

$$\boxed{V_S = \sqrt{V_R^2 + V_C^2}}$$

Now we can check our calculations:

$$V_S = \sqrt{V_R^2 + V_C^2}$$

$$V_S = \sqrt{2.72V^2 + 4.19V^2}$$

$$V_S = 4.995V$$

From this answer we can see that our calculations look good.

With all this information about the circuit, it's also possible to calculate the powers around the circuit. However, the subject of power is dealt with separately in another section.

Practise calculating the circuit current and potential differences in RC circuits by trying the following questions.

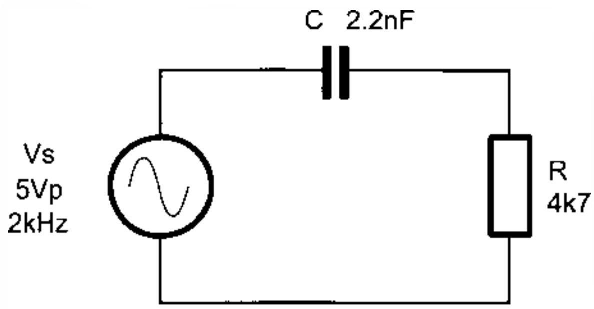


Figure 5

1. Calculate the capacitor's capacitive reactance (X_C).

2. Calculate the impedance (Z) of the circuit.

3. Calculate the circuit current (I).

4. Calculate the potential difference across the capacitor (V_C).

5. Calculate the potential difference across the resistor (V_R).

6. Check your answers by using V_R and V_C to calculate V_S.

7. Draw the phasor diagram for the current and all voltages in the circuit including V_S.

If you compare your phasor diagram above with the phasor diagram in Figure 4 (page 9-5) you may notice that the position of the phasor for V_S is dependant on the supply's output frequency. At lower frequencies, the capacitive reactance becomes relatively large and dominates the circuit so the phasor for V_S is closer to the phasor for V_C. At higher frequencies the capacitive reactance becomes relatively small and so the phasor for V_S is closer to the phasor for V_R.

Analysing RL circuits

Let's analyse the RL circuit in Figure 6 below by calculating the current and potential difference across the inductor and resistor.

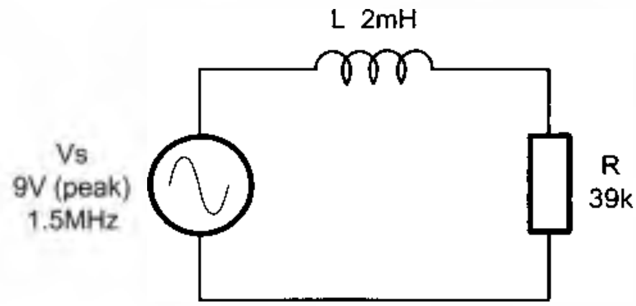


Figure 6 *A series RL circuit*

Procedure:

1. Find the reactance of the inductor (X_L).

   This is found using the equation: $X_L = 2\pi fL$. In this example, X_L is 18.85kΩ.

2. Find the total circuit impedance (Z).

   This is found using the equation: $Z = \sqrt{R^2 + X_L^2}$. In this example Z is 43.32kΩ.

3. Find the circuit current (I).

   This is found using Ohm's Law: $I = \frac{E}{Z}$. In this example I is 207.8μA (peak).

4. Find the potential difference across the resistor (V_R).

   This is found using Ohm's Law: $V_R = I \times R$. In this example V_R is 8.1V (peak).

5. Find the potential difference across the inductor (V_L).

   This is found using Ohm's Law: $V_L = I \times X_L$. In this example V_L is 3.92V (peak).

6. Check the calculations.

   This is done using the equation: $V_S = \sqrt{V_R^2 + V_L^2}$. In this example, V_S checks out to be 8.997V and so the calculations are probably correct.

Figure 7 below shows the current and potential differences that have just been calculated in a phasor diagram. As the circuit is a series circuit, current is the reference.

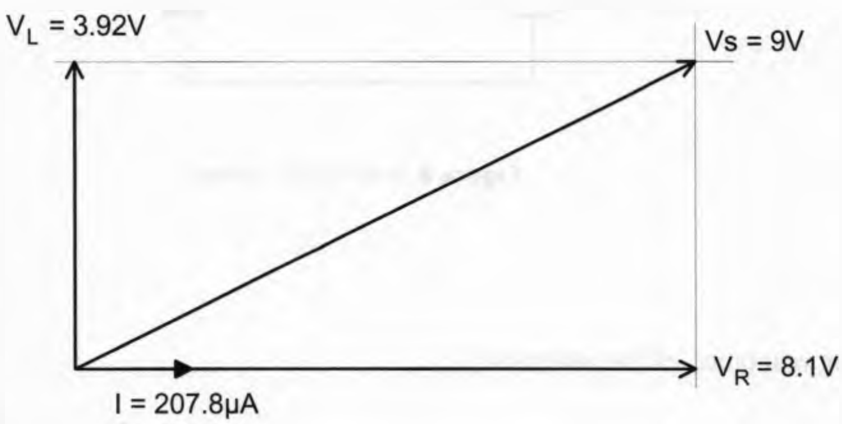


Figure 7 *The phasor diagram showing current and voltages around the circuit of Figure 6*

As with RC circuits it's also possible to calculate the powers around the circuit. However, the subject of power is dealt with separately in another section.

Practise calculating the circuit current and potential differences in RL circuits by trying the following questions.

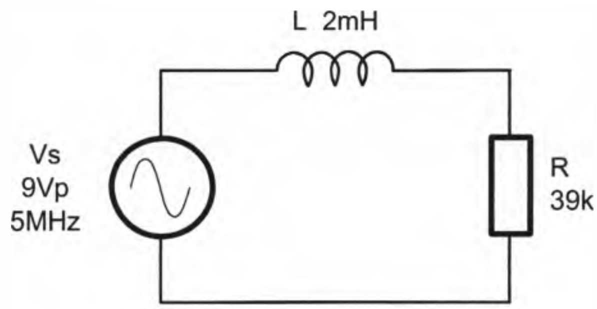


Figure 8

1. Calculate the inductor's inductive reactance (X_L).

2. Calculate the impedance (Z) of the circuit.

3. Calculate the circuit current (I).

4. Calculate the potential difference across the inductor (V_L).

5. Calculate the potential difference across the resistor (V_R).

6. Check your answers by using V_R and V_L to calculate V_S.

7. Draw the phasor diagram for the current and all voltages in the circuit including V_S.

If you compare your phasor diagram above with the phasor diagram in Figure 7 (page 9-10) you'll notice that the position of the phasor for V_S is dependant on the supply's output frequency. At higher frequencies, the inductive reactance becomes relatively large and dominates the circuit so the phasor for V_S is closer to the phasor for V_L. At lower frequencies the inductive reactance becomes relatively small and so the phasor for V_S is closer to the phasor for V_R.

Analysing RLC circuits

Let's analyse the RLC circuit in Figure 9 below by calculating the current and potential difference across the inductor, capacitor and resistor.

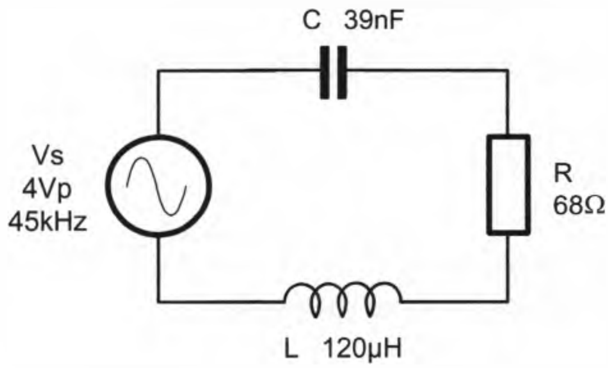


Figure 9 *A series RLC circuit*

Procedure:

1. Find the reactance of the inductor (X_L).

   This is found using the equation: $X_L = 2\pi fL$. In this example X_L is 33.9Ω.

2. Find the reactance of the capacitor (X_C).

   This is found using the equation: $X_C = \frac{1}{2\pi fC}$. In this example X_C is 90.7Ω.

3. Find the total circuit impedance (Z).

   This is found using the equation: $Z = \sqrt{R^2 + (X_C - X_L)^2}$. In this example Z is 88.6Ω.

4. Find the circuit current (I).

   This is found using Ohm's Law: $I = \frac{E}{Z}$. In this example I is 45.2mA (peak).

5. Find the potential difference across the resistor (V_R).

   This is found using Ohm's Law: $V_R = I \times R$. In this example V_R is 3.1V (peak).

6. Find the potential difference across the inductor (V_L).

   This is found using Ohm's Law: $V_L = I \times X_L$. In this example V_L is 1.5V (peak).

7. Find the potential difference across the capacitor (V_C).

   This is found using Ohm's Law: $V_C = I \times X_C$. In this example V_C is 4.1V (peak).

8. Check the calculations.

   This is done using the equation: $V_S = \sqrt{V_R^2 + (V_C - V_L)^2}$. In this example, V_S checks out to be 4.045V so the calculations are probably correct.

Figure 10 below shows the current and potential differences that have just been calculated in a phasor diagram. Notice that, to find V_S, the value of V_L must first be subtracted from V_C because these two voltages are in opposite phases to each other.

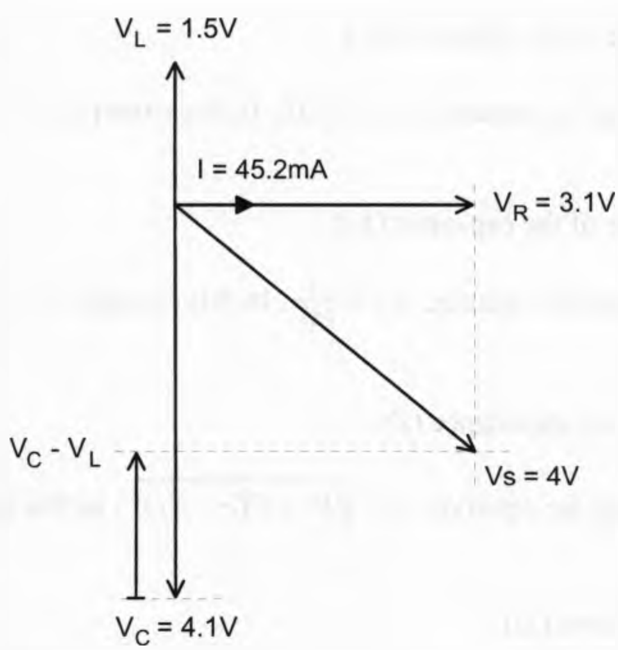


Figure 10 *The phasor diagram showing current and voltages around the circuit of Figure 9*

Practise calculating the circuit current and potential differences in RL circuits by trying the following questions.

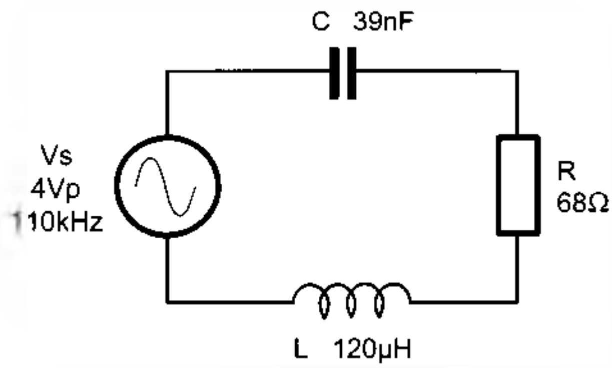


Figure 11

1. Calculate the inductor's inductive reactance (X_L).

2. Calculate the capacitor's capacitive reactance (X_C).

3. Calculate the impedance (Z) of the circuit.

4. Calculate the circuit current (I).

5. Calculate the potential difference across the resistor (V_R).

6. Calculate the potential difference across the inductor (V_L).

7. Calculate the potential difference across the capacitor (V_C).

8. Check your answers by using V_R, V_L and V_C to calculate V_S.

9. Draw the phasor diagram for the current and all voltages in the circuit including V_S.

Questions 10 to 18 refer to the circuit in Figure 12 below

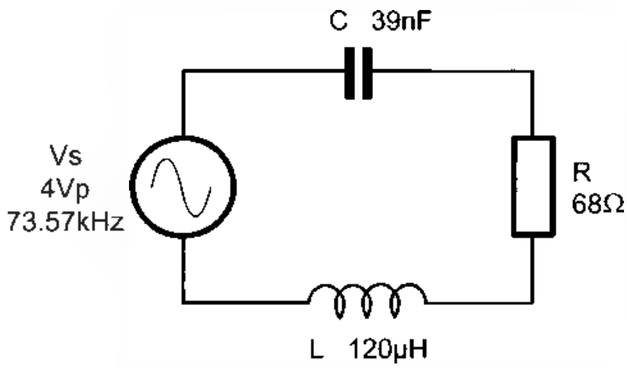


Figure 12

10. Calculate the inductor's inductive reactance (X_L).

____

____

11. Calculate the capacitor's capacitive reactance (X_C).

____

____

12. Calculate the impedance (Z) of the circuit.

____

____

13. Calculate the circuit current (I).

____

____

14. Calculate the potential difference across the resistor (V_R).

____

____

15. Calculate the potential difference across the inductor (V_L).

16. Calculate the potential difference across the capacitor (V_C).

17. Check your answers by using V_R, V_L and V_C to calculate V_S.

18. Draw the phasor diagram for the current and all voltages in the circuit including V_S.

Resonance

The last circuit (Figure 12) demonstrates an example of a curious effect that occurs in RLC circuits. At one particular frequency the reactances of the inductor and the capacitor are equal. This means that the potential difference across the two components are equal. And, as the two potential differences are 180° out of phase they fully cancel out each other. This effect is called *resonance* and the frequency at which it occurs is called the *resonant frequency*.

At the resonant frequency the only component that appears to be in the circuit is the resistor. In other words, the circuit looks purely resistive. That being the case, the supply voltage is in phase with the potential difference across the resistor.

Resonance will be revisited in some detail later in this subject.

Student notes

Skill practice 9

Practise measuring AC voltages and phase shifts in series RL, RC and RLC circuits using an oscilloscope

This exercise is practise for the sorts of skills you may be required to perform in a practical test. Remember, in any practical tests you will be working alone so make sure that you can perform all the steps. It should take you about 1¼ hours to complete this exercise.

Equipment

- Interface panel
- 2.5mH inductor
- 1nF capacitor
- 1kΩ ¼W resistor
- three BNC to banana-plug leads
- banana leads

> **Remember:**
>
> Follow TAFE NSW WHS guidance at all times!

Work tasks

1. Read your WHS responsibilities at the top of the form below. Then conduct a WHS risk assessment and record your findings in the space provided.

Responsibilities of students under the Model WHS Act: s28

- Take reasonable care for your own health and safety by working safely at all times
- Take reasonable care to ensure that your acts or omissions don't put the health and safety of others at risk
- Follow all TAFE NSW WHS guidance and comply with all reasonable instructions from TAFE NSW staff to assist them in complying with the TAFE NSW WHS requirements
- In addition to the above, you must:
  - use and maintain machinery, tools and all other equipment properly and safely
  - ensure that your work area is free of hazards
  - notify a TAFE NSW staff member of actual or potential hazards
  - wear/use prescribed safety equipment
  - take notice of any safety signs and adhere to their instructions

Risks involved in this activity include:	**Control measures:**
Trip hazards (eg students bags) Objects dropped on feet (while equipment is taken to and from workbenches).	Move bags and other objects from walkways Plan lifting of equipment
Others: ______________________ ______________________ ______________________	Other: ______________________ ______________________ ______________________

My signature here indicates that I have read and understand my responsibilities under the Model WHS Act s28 (detailed above). I have also conducted a risk assessment before undertaking this activity and have identified measures to control these risks and have implemented them.

Signature: ______________________ Date: ______________________

2. Gather the equipment needed for this exercise.

3. Wire the circuit of Figure 1 on the interface panel.

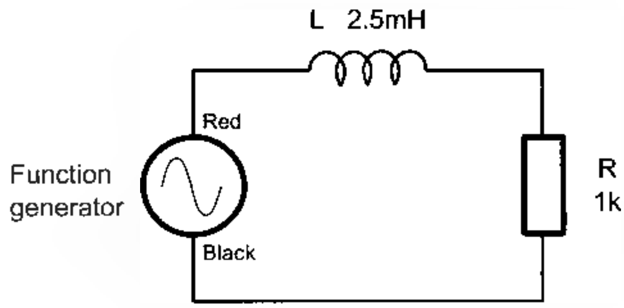


Figure 1

4. Set the function generator's output for a 100kHz sinewave.

5. Set the amplitude of function generator's output to maximum.

6. Accurately measure the function generator's peak-to-peak output voltage using the CRO. Record your measurement in Table 1.

7. Accurately measure and record the peak-to-peak potential difference across the resistor (V_R) using the CRO.

8. Swap the position of the resistor and the inductor.

9. Accurately measure and record the peak-to-peak potential difference across the inductor (V_L) using the CRO.

Table 1

V_S (Step 6)	V_R (Step 7)	V_L (Steps 8 & 9)

10. Check your measurements are correct by using your values of V_R and V_L to calculate V_S using the equation: $V_S = \sqrt{V_R^2 + V_L^2}$.

Question 1
Why can't you simply **add** V_R and V_L together to calculate V_S?

Question 2
Are your measured and calculated values of V_S the same? What might explain any differences?

Question 3
Why was it necessary to swap the resistor and inductor to measure the potential difference across the inductor?

11. Accurately measure the phase difference between V_L and V_S. Note whether V_L leads or lags V_S. Record this information in Table 2 below.

12. Swap the position of the resistor and the inductor again.

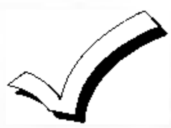
13. Accurately, measure and record the phase difference between V_S and V_R. Note whether V_S leads or lags V_R.

Table 2

Step 11		Steps 12 & 13	
V_L leads/lags V_S?	**Phase difference between V_S and V_L**	**V_S leads/lags V_R?**	**Phase difference between V_S and V_R**

Question 4

Draw the phasor diagram showing the supply voltage, circuit current (don't worry about calculating its value) and the potential difference across the resistor and inductor using current as the reference. [Tip: to make drawing the diagram easier, draw the current phasor first then draw the voltage phasors in the following order V_R, V_S then V_L.]



The teacher needs to check your work at this point...

14. Wire the circuit of Figure 2.

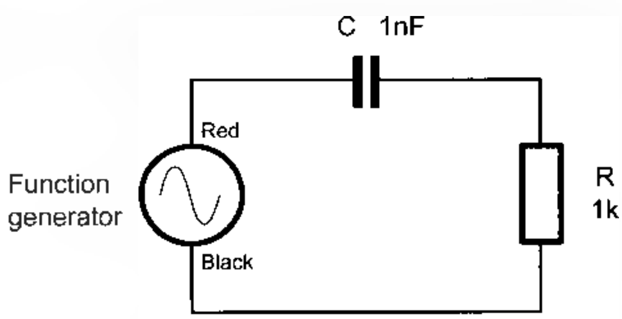


Figure 2

15. Adjust the function generator for a 250kHz sinewave output at maximum voltage.

16. Accurately measure the function generator's peak-to-peak output voltage using the CRO. Record your measurement in Table 3.

17. Accurately measure and record the peak-to-peak potential difference across the resistor (V_R) using the CRO.

18. Swap the position of the resistor and the capacitor.

19. Accurately measure and record the peak-to-peak potential difference across the capacitor (V_C) using the CRO.

Table 3

V_S	V_R	V_C

20. Check your measurements are correct by using your values of V_R and V_C to calculate V_S using the equation: $V_S = \sqrt{V_R^2 + V_C^2}$.

21. Accurately measure the phase difference between V_C and V_S. Note whether V_C leads or lags V_S. Record this information in Table 4.

22. Swap the position of the resistor and the capacitor again.

23. Accurately, measure and record the phase difference between V_S and V_R. Note whether V_S leads or lags V_R.

Table 4

V_C leads/lags V_S?	Phase difference between V_S and V_C	V_S leads/lags V_R?	Phase difference between V_S and V_R

Question 5

Draw the phasor diagram showing the supply voltage, circuit current (don't worry about calculating its value) and the potential difference across the resistor and capacitor using current as the reference. [Tip: to make drawing the diagram easier, draw the current phasor first then draw the voltage phasors in the following order V_R, V_S then V_C.]

The teacher needs to check your work at this point...

24. Wire the circuit of Figure 3.

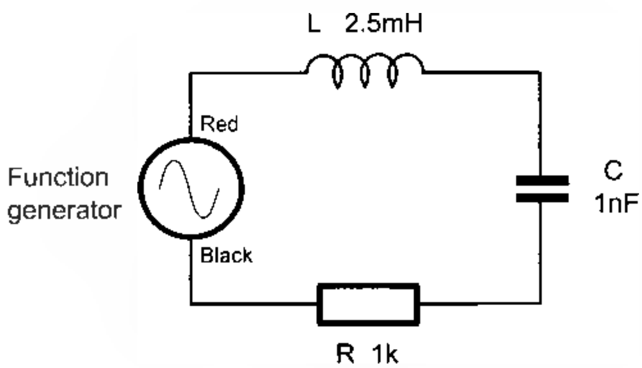


Figure 3

25. Adjust the function generator for a 150kHz sinewave output at maximum voltage.

26. Accurately measure and record the function generator's peak-to-peak output voltage using the CRO. Record your measurement in Table 5 (on the next page).

27. Accurately measure and record the peak-to-peak potential difference across the resistor (V_R) using the CRO.

28. Swap the position of the resistor and the capacitor.

29. Accurately measure and record the peak-to-peak potential difference across the capacitor (V_C) using the CRO.

30. Swap the position of the inductor and the capacitor.

31. Accurately measure and record the peak-to-peak potential difference across the inductor (V_L) using the CRO.

32. Check your measurements are correct by using your values of V_R and V_C to calculate V_S using the equation: $V_S = \sqrt{V_R^2 + (V_L - V_C)^2}$.

33. Accurately measure the phase difference between V_L and V_S. Note whether V_L leads or lags V_S. Record this information in Table 6 (on the next page).

34. Swap the position of the inductor and the capacitor again.

35. Accurately measure the phase difference between V_C and V_S. Note whether V_C leads or lags V_S. Record this information in Table 6.

36. Swap the position of the capacitor and the resistor.

37. Accurately, measure and record the phase difference between V_S and V_R. Note whether V_S leads or lags V_R.

Table 5

V_S	
V_R	
V_C	
V_L	

Table 6

V_L leads/lags V_S?	
Phase difference between V_S and V_L	
V_C leads/lags V_S?	
Phase difference between V_S and V_C	
V_S leads/lags V_R?	
Phase difference between V_S and V_R	

Question 6

Draw the phasor diagram showing the supply voltage, the circuit current (don't worry about calculating its value) and the potential difference across the resistor, capacitor and inductor using current as the reference. [Tip: to make drawing the diagram easier, draw the current phasor first then draw the voltage phasors in the following order V_R, V_S, V_L then V_C.]

The teacher needs to check your work at this point...

38. Repeat steps 26 to 37 for a frequency of 60kHz recording your results in Tables 7 and 8 below.

Table 7

V_S	
V_R	
V_C	
V_L	

Table 8

V_L leads/lags V_S?	
Phase difference between V_S and V_L	
V_C leads/lags V_S?	
Phase difference between V_S and V_C	
V_S leads/lags V_R?	
Phase difference between V_S and V_R	

Question 7

Draw the phasor diagram showing the supply voltage, the circuit current (don't worry about calculating its value) and the potential difference across the resistor, capacitor and inductor using current as the reference. [Tip: to make drawing the diagram easier, draw the current phasor first then draw the voltage phasors in the following order V_R, V_S, V_c then V_L.]

The teacher needs to check your work at this point...

39. Repeat steps 26 to 37 at the frequency where the voltage across the resistor is maximum (which should be about 100kHz). Record your results in Tables 9 and 10 below.

Table 9

V_S	
V_R	
V_C	
V_L	

Table 10

V_L leads/lags V_S?	
Phase difference between V_S and V_L	
V_C leads/lags V_S?	
Phase difference between V_S and V_C	
V_S leads/lags V_R?	
Phase difference between V_S and V_R	

Question 8

Draw the phasor diagram showing the supply voltage, the circuit current (don't worry about calculating its value) and the potential difference across the resistor, capacitor and inductor using current as the reference. [Tip: to make drawing the diagram easier, draw the current phasor first then draw the voltage phasors in the following order V_R, V_S, V_c then V_L.]

The teacher needs to check your work at this point...

Student notes

Review questions

Answer these questions to check your understanding of what you have for this chapter. Doing this will also help to prepare you for the tests.

1. For the circuit of Figure 1, calculate:

   (a) X_L
   (b) Z
   (c) I
   (d) V_R
   (e) V_L

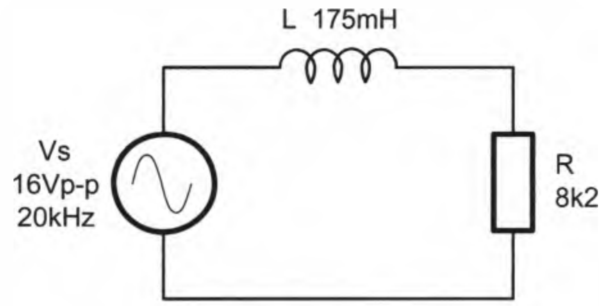


Figure 1

2. Draw the phasor diagram showing the circuit current and all voltages around the circuit.

3. For the circuit of Figure 2, if the potential difference across the resistor (V_R) is 4.2V (peak), then calculate:

   (a) X_L

   (b) I

   (c) V_L

   (d) V_S

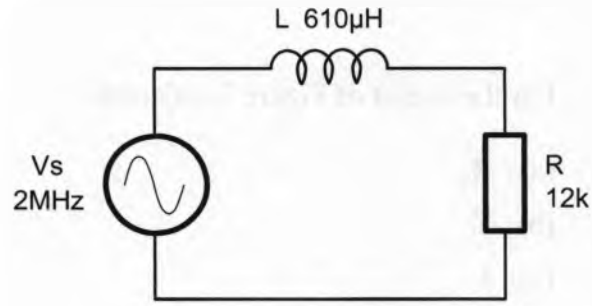


Figure 2

4. Draw the phasor diagram showing the circuit current and all voltages (V_S, V_R and V_L) around the circuit.

5. For the circuit of Figure 3, if the potential difference across the inductor (V_L) is 8.7V, then calculate:

(a) X_L

(b) I

(c) V_R

(d) V_S

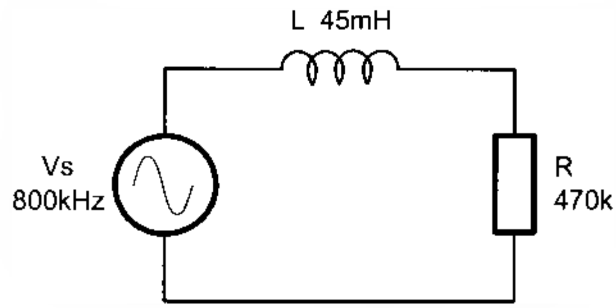


Figure 3

6. Draw the phasor diagram showing the circuit current and all voltages (V_S, V_R and V_L) around the circuit.

7. For the circuit of Figure 4, calculate:

   (a) X_C
   (b) Z
   (c) I
   (d) V_R
   (e) V_C

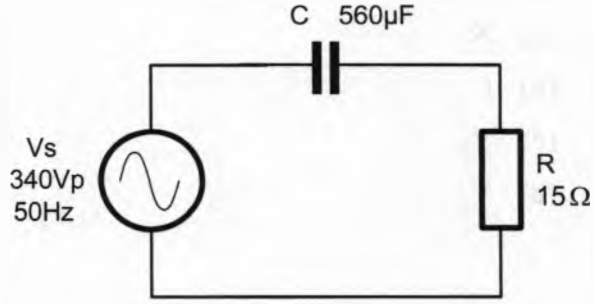


Figure 4

8. Draw the phasor diagram showing the circuit current and all voltages around the circuit.

9. For the circuit of Figure 5, if the potential difference across the resistor (V_R) is 9.5V, then calculate:

   (a) X_C

   (b) I

   (c) V_C

   (d) V_S

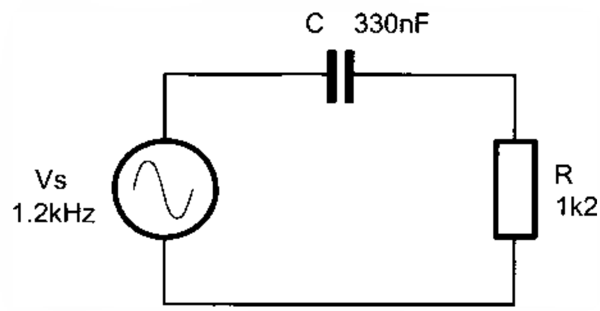


Figure 5

10. Draw the phasor diagram showing the circuit current and all voltages around the circuit.

11. For the circuit of Figure 6, if the potential difference across the capacitor (V_C) is 22V (peak-to-peak), then calculate:

(a) X_C

(b) I

(c) V_R

(d) V_S

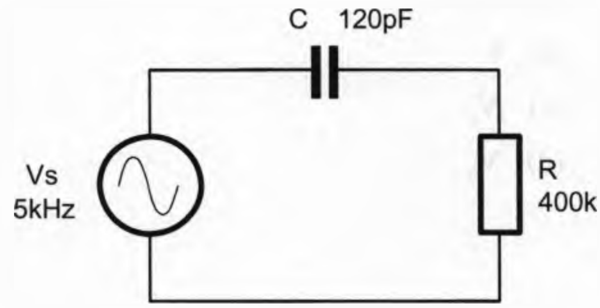


Figure 6

12. Draw the phasor diagram showing the circuit current and all voltages around the circuit.

13. For the circuit of Figure 7, calculate:

(a) X_L

(b) X_C

(c) Z

(d) I

(e) V_R

(f) V_L

(g) V_C

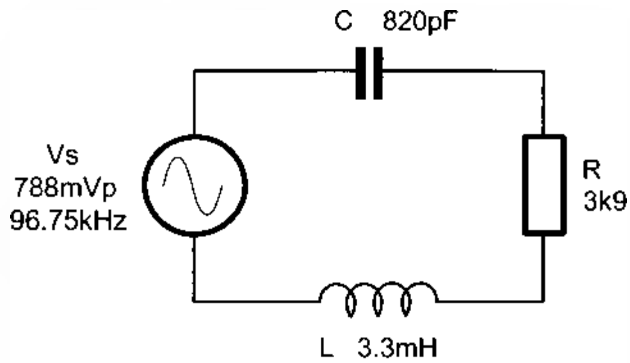


Figure 7

14. Draw the phasor diagram showing the circuit current and all voltages around the circuit.

15. For the circuit of Figure 8, if the potential difference across the resistor (V_R) is 7V (peak), then calculate:

(a) X_L

(b) X_C

(c) I

(d) V_L

(e) V_C

(f) V_S

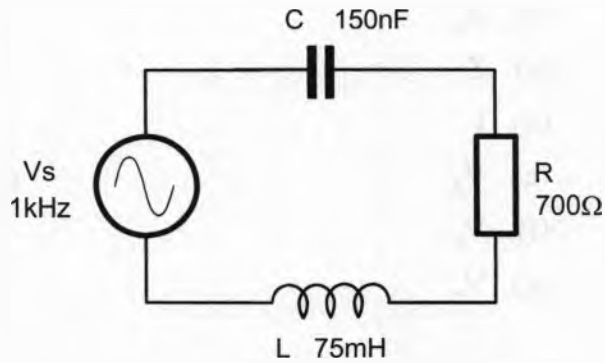


Figure 8

16. Draw the phasor diagram showing the circuit current and all voltages around the circuit.

17. For the circuit of Figure 9, if the potential difference across the inductor (V_L) is 650mV (peak), then calculate:

    (a) X_L
    (b) X_C
    (c) I
    (d) V_R
    (e) V_C
    (f) V_S

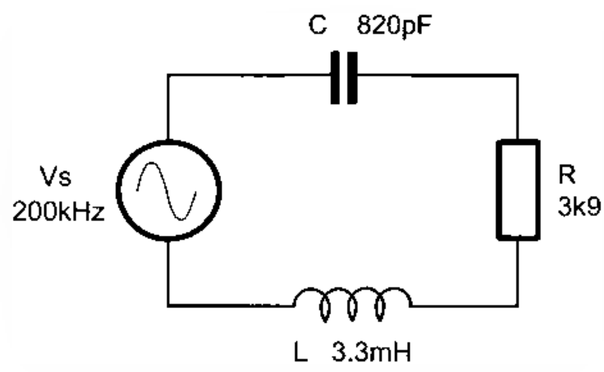


Figure 9

18. Draw the phasor diagram showing the circuit current and all voltages around the circuit.

19. For the circuit of Figure 10, calculate:

(a) X_L
(b) X_C
(c) Z
(d) I
(e) V_R
(f) V_L
(g) V_C

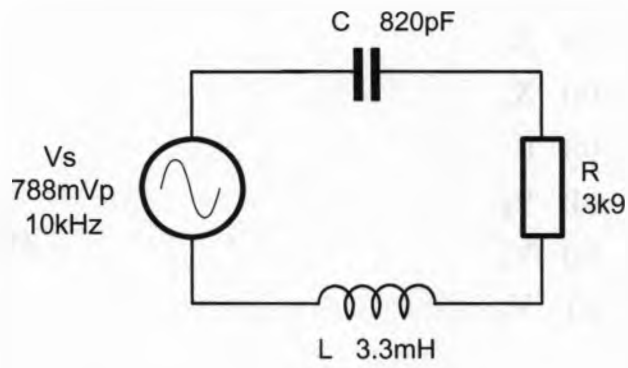


Figure 10

20. Draw the phasor diagram showing the circuit current and all voltages around the circuit.

Section 10 Power in AC circuits with reactive components

Purpose To deepen your understanding of the operation of inductors and capacitors in AC circuits.

Objectives At the end of this section you should be able to:

- Define the terms *real power*, *reactive power* and *apparent power*
- State the symbol for the above and their unit of measurement
- Explain why (ideal) inductors and capacitors don't dissipate power when connected to a sinusoidal source
- Calculate the real, reactive and apparent powers in an RL, RC or RLC circuit given the EMF voltage, EMF frequency and component values
- Explain the term *power factor*
- Calculate the power factor of an RL or RC circuit given the EMF voltage, EMF frequency and component values

Introduction

Generally speaking, the power in AC circuits is an important and interesting issue. For technicians, the way that power is exchanged between inductors and capacitors in AC circuits is crucial to understanding the operation of many circuits. For electricians, the issue of power factor and power factor correction is important to the installation of electrical equipment especially in industrial applications. As this subject is common to both the electronic and electrical trades this section discusses both issues.

Instantaneous power dissipation in resistive circuits

Recall that the power dissipated by resistors can be calculated using one of the three equations below (depending on the information available):

$$P = I \times V \qquad P = \frac{V^2}{R} \qquad P = I^2 \times R$$

Recall also that the notes in this workbook have stressed that RMS values of voltage and current **must** be used when performing power calculations (read Section 6 for an explanation).

That said, instantaneous values of voltage and/or current can be used to determine the instantaneous power dissipated by the resistor. Although this is not something that a technician would do in their day-to-day work, it's highly relevant to the discussion here.

Figure 1 below shows a simple single-resistor circuit connected to a 10V peak supply.

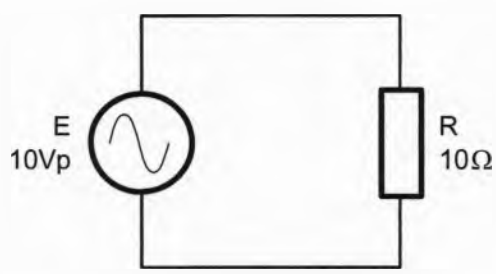


Figure 1 *A simple single-resistor circuit*

Figure 2 on the next page shows the graph of the power dissipated by the resistor for one cycle of the EMF voltage calculated using the instantaneous values of EMF voltage and circuit current and the equation $p = i \times v$ (by convention, lower case letters are usually used when the values are instantaneous but this is not something you'd be asked to recall in a test for this subject).

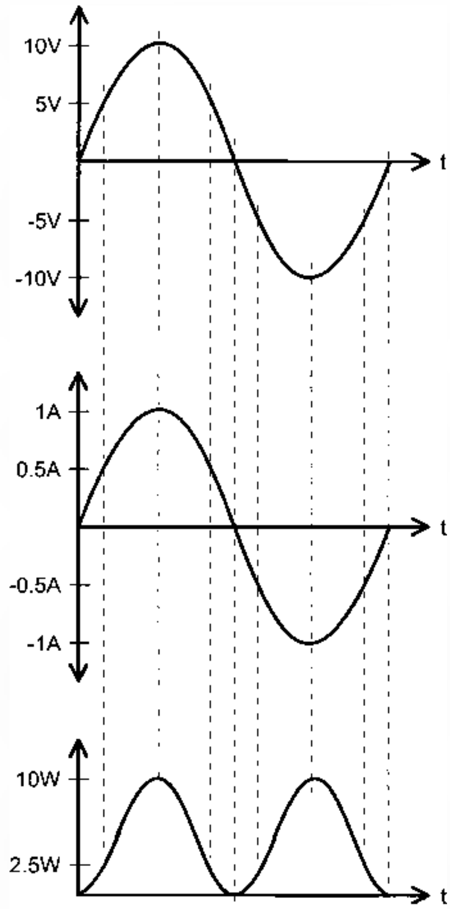


Figure 2

The important thing to notice about the graph of power dissipated by the resistor is that the power is always positive. This is true even during the negative half cycle of the EMF voltage. The fact that the power dissipation is always positive is telling us that power is only ever transferred in one direction, from the EMF to the resistor.

Now let's see what happens to power in purely inductive and capacitive circuits.

Instantaneous power dissipation in inductive circuits

Figure 3 below shows a simple single-inductor circuit connected to a 10V peak supply.

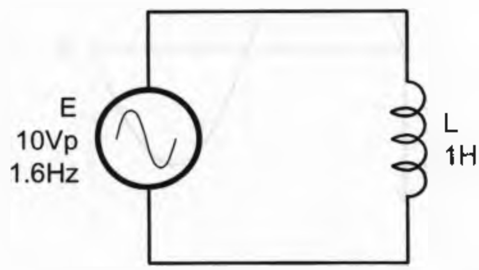


Figure 3 *A simple single-inductor circuit*

An inductance of 1H and an EMF frequency of 1.6Hz has been chosen for the circuit so that the inductor's reactance is 10Ω. This gives us a convenient comparison with the resistive circuit in Figure 1 because the peak circuit current for this circuit must be 1A as well.

Recall that the potential difference across an inductor leads the circuit current by 90°. This has important implications for the instantaneous power as shown in Figure 4 to the right.

Notice that for half of the time the power is positive (rising to an instantaneous peak of 5W) but for the other half of the time the power is negative (rising to an instantaneous peak of -5W).

What is negative power? The negative sign simply denotes the fact that during this time the transfer of energy is effectively reversed and moves from the inductor to the source (that is, the EMF).

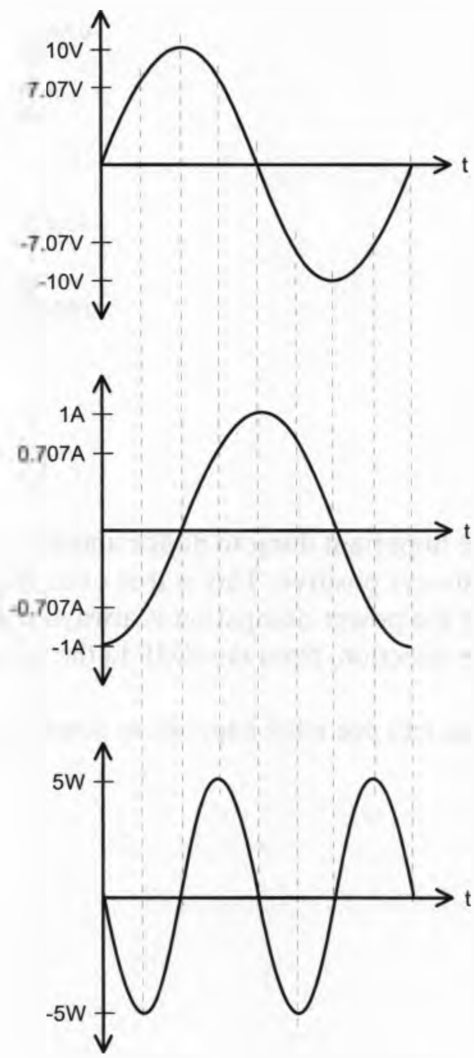


Figure 4

This is possible because inductors store energy as an electromagnetic field. When the circuit current reaches maximum (in either direction) and subsequently drops, the electromagnetic field about the inductor collapses. This induces a current back into the circuit. In other words, during this time the inductor acts as an EMF that reduces the electrical burden of the circuit on the actual EMF effectively returning energy to the EMF.

The implication of this is significant. As the inductor takes energy from the sinusoidal source for half a cycle and returns it during the other half, its power across the entire cycle is zero (this assumes an ideal inductor - that is, one with no DC resistance). Put another way, inductors don't actually "dissipate" power (that is, convert it to heat).

Reactive power in inductors

The previous discussion leads us to an interesting inconsistency. If you calculate the inductor's power using RMS values (as you're required to do for resistors), you get 5 and not 0W. Proof: The RMS value of the EMF voltage is 7.07V and, as the inductor's reactance is 10Ω, the RMS value of circuit current is 0.707A. According to the equation $P = I \times V$ the power "dissipated" by the inductor is 5.

This is clearly wrong because we have just seen that the inductor's average power is zero. However, this calculation is useful (as will be explained) and so the multiplication of the RMS potential difference across an inductor with the RMS current through it is called *reactive power* and is denoted by the letter Q. That is, $Q = I \times V_L$.

As reactive power is energy that is not dissipated, the watt cannot be used for its unit of measurement. Instead, the *volt-ampere reactive* is used and is abbreviated to *var*. So, the reactive power (Q) of the inductor in Figure 3 is: $Q = I \times V_L = 7.07V \times 0.707A = 5\ vars$.

As an aside, Q can also be calculated using $Q = \frac{V_L^2}{X_L}$ and $Q = I^2 X_L$ as long as RMS values of V_L or I are used. Proof: $Q = I^2 X_L = 0.0707A^2 \times 10\Omega = 5\ vars$.

Instantaneous power dissipation in capacitive circuits

Figure 5 below shows a simple single-capacitor circuit connected to a 10V peak supply.

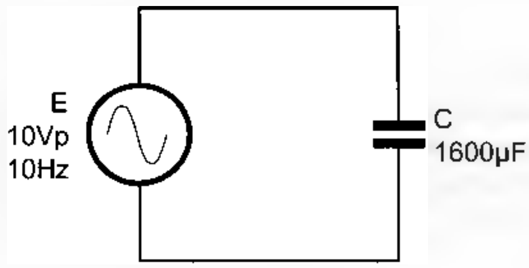


Figure 5 *A simple single-capacitor circuit*

A capacitance of 1,600μF and an EMF frequency of 10Hz has been chosen for the circuit so that the capacitor's reactance is 10Ω. This gives us a convenient comparison with the resistive circuit in Figure 1 and the inductive circuit in Figure 3 because the peak circuit current of 1A is the same in all cases.

However, recall that the potential difference across a capacitor lags the circuit current by 90°. The effect of this on power is shown in Figure 6 to the right.

Notice that, as with the inductor, the capacitor's power is positive for half a cycle and negative for the other half. That is, the capacitor takes energy from the source for half a cycle and returns it during the other half.

This is possible because capacitors store energy as an electrostatic field. When the circuit current reaches maximum (in either direction) and subsequently drops, the capacitor discharges and converts the electrostatic field back to electrical energy in the form of current back into the circuit. In other words, during this time the capacitor acts as an EMF that reduces the electrical burden of the circuit on the actual EMF effectively returning energy to the EMF.

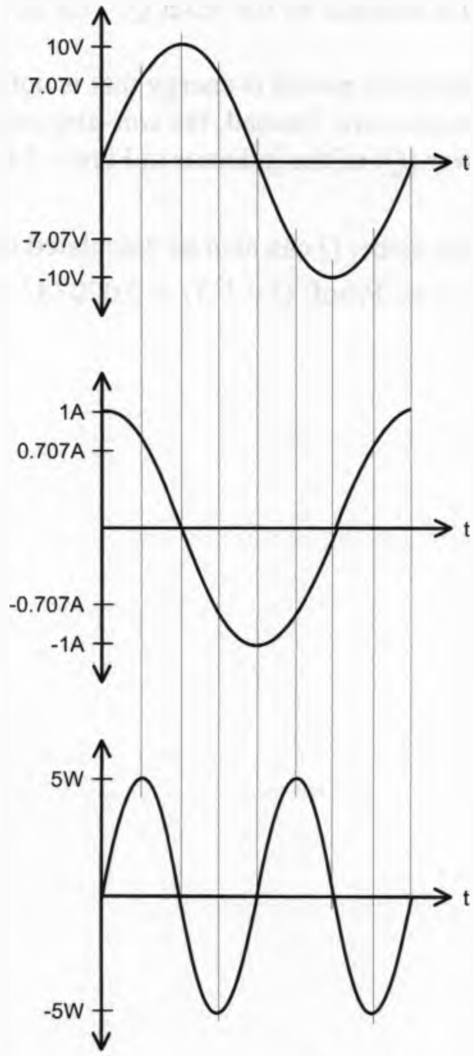


Figure 6

The implication of this is the same as for inductors - the average power dissipated by a capacitor connected to a sinusoidal source is zero.

Reactive power in capacitors

As with inductors, the reactive power of capacitors can be calculated using the RMS values of the potential difference across the capacitor and the circuit current. For this circuit, the reactive power is:

$$Q = I \times V_C$$

$$Q = 0.707A \times 7.07V$$

$$Q = 5\ vars$$

Reactive power can also be calculated using $Q = \frac{V_C^2}{X_C}$ and $Q = I^2 \times X_C$ as long as RMS values of V_C or I are used. Remember though, this is not power that is dissipated.

Power in RL and RC circuits

So far, we have seen that resistors dissipate power but inductors and capacitors don't. Now let's consider what happens in RL and RC circuits. Figures 7a and 7b below show an RL and an RC circuit. Beneath them is a sufficient analysis of the circuits to find the power dissipated by the resistor and the reactive power of the inductor or capacitor.

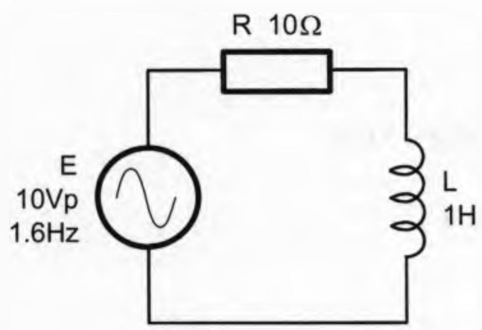


Figure 7a

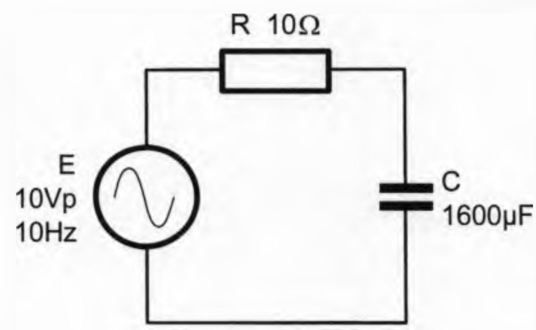


Figure 7b

$$X_L = 2\pi f L$$

$$X_L = 2\pi \times 1.6Hz \times 1H$$

$$X_L = 10\Omega$$

$$Z = \sqrt{R^2 + X_L^2}$$

$$Z = \sqrt{10\Omega^2 + 10\Omega^2}$$

$$Z = 14.14\Omega$$

$$X_C = \frac{1}{2\pi f C}$$

$$X_C = \frac{1}{2\pi \times 10Hz \times 1600\mu F}$$

$$X_C = 10\Omega$$

$$Z = \sqrt{R^2 + X_C^2}$$

$$Z = \sqrt{10\Omega^2 + 10\Omega^2}$$

$$Z = 14.14\Omega$$

As Z is the same for both circuits, the current must be the same for both circuits.

$$I_{RMS} = \frac{E}{Z}$$

$$I_{RMS} = \frac{7.07V}{14.14\Omega}$$

$$I_{RMS} = 0.5A$$

And the power dissipated by the resistor must be the same for both circuits too.

$$P_R = I^2R$$

$$P_R = 0.5A^2 \times 10\Omega$$

$$P_R = 2.5W$$

Finally, the reactive power dissipated by the inductor and capacitor can be found.

$$Q = I^2X_L \qquad Q = I^2X_C$$

$$Q = 0.5A^2 \times 10\Omega \qquad Q = 0.5A^2 \times 10\Omega$$

$$Q = 2.5\ vars \qquad Q = 2.5\ vars$$

Importantly, as inductors and capacitors don't dissipate their power, the only power dissipated by the circuit is the power dissipated by the resistor. For this reason, the resistor's power is called *real power* (as well as *true power*, *resistive power* and *wattage*).

Apparent power
This discussion brings us to a second inconsistency. If you calculate the power dissipated by the entire circuit using RMS values of applied voltage and circuit current, you get 3.54 and not 2.5W. Proof: The RMS value of the EMF voltage is 7.07V and the RMS value of circuit current is 0.5A. According to the equation $P = I \times V$ the power "dissipated" by the circuit is 3.54.

This is clearly wrong. However, the calculation is useful (as will be explained) so the multiplication of the RMS EMF voltage with the RMS circuit current is called *apparent power* and is denoted by the letter S. That is, $S = I \times V$.

As apparent power consists of reactive power (which is energy that is not dissipated), the watt cannot be used for its unit of measurement. However, apparent power also consists of real power so the *volt-ampere reactive* cannot be used either. Instead, the *voltampere* (VA) is used. So, the apparent power (S) of the circuits in Figures 7a and 7b is: $S = I \times V = 0.5A \times 7.07V = 3.54VA$.

As an aside, Q can also be calculated using $S = \frac{V^2}{Z}$ and $S = I^2 \times Z$ as long as RMS values of EMF voltage or circuit current are used. Proof: $S = I^2 \times Z = 0.5A^2 \times 14.14\Omega = 3.54VA$.

Usefully, apparent power can also be found using the equation: $S = \sqrt{P_R^2 + Q^2}$ because real power, reactive power and apparent power form a power triangle (we'll not get you to draw one of these though). Proof: $S = \sqrt{P_R^2 + Q^2} = \sqrt{2.5W^2 + 2.5^2 vars} = 3.54VA$.

Power factor

As the previous discussion shows, the apparent power of a circuit is higher than the real or true power (the power dissipated by the resistor). This can often be the case. For reasons that will be explained, it's important to quantify the relationship between these two powers. This requirement gives us a quantity called *power factor* (*pf* or *cosφ*). Power factor is simply the ratio of real power to apparent power and is calculated using the equation:

$$\boxed{pf = \frac{P_R}{S}}$$

The power factor of the circuits in Figures 7a and 7b is:

$$pf = \frac{P_R}{S}$$

$$pf = \frac{2.5W}{3.54VA}$$

$$pf = 0.706$$

In the case of the RL circuit's power factor, it is said to be "0.706 lagging" because the circuit current in an RL circuit lags the source voltage. The power factor of the RC circuit is said to be "0.706 leading".

Practise analysing the powers in a reactive AC circuit for yourself by trying the following questions.

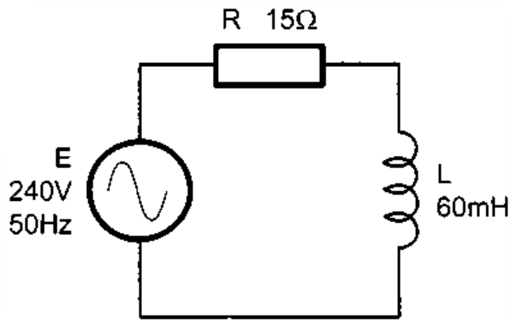


Figure 8

1. Calculate the inductor's inductive reactance (X_L).

2. Calculate the circuit's impedance (Z).

3. Calculate the RMS circuit current (I).

4. Calculate the real power dissipated by the circuit (P *or* P_R).

5. Calculate the inductor's reactive power (*Q*).

6. Calculate the circuit's apparent power (*S*).

7. Calculate the circuit's power factor (*pf*).

Power factor correction - This topic is not tested for CII and CIII students

The heading *power factor correction* implies that there is a right and wrong value for power factor. From the perspective of the electrical energy distribution companies, this is absolutely true. For these organisations, the optimal power factor is a figure approaching 1 and anything below this (either leading or lagging) must be corrected.

There's a very good reason for this. To understand it, you need a little background information. The overall industrial and domestic load for power distribution systems is resistive and inductive (rather than purely resistive or resistive and capacitive). This is due in large part to the number of motors used in machinery and the compressors used in refrigeration systems. There are lots of them and they require much more power than most other types of load.

Figure 9a below shows a motor connected to a source and 9b shows the equivalent circuit. As you can see, a motor equates to an RL circuit. The inductance is due to the motor's windings and the resistance is due to the DC resistance of the wire used to make them. (Note: Although the resistance of copper wire is small, it can add up to five, ten or more Ohms for motor windings because the wire is so long.)

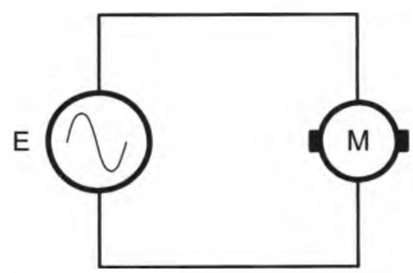


Figure 9a *A motor connected to an AC source*

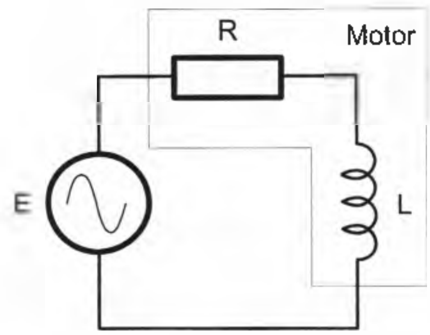


Figure 9b *The equivalent for 9a*

As the previous discussion has shown, only the resistive component of the motor's winding dissipates power. The power required by the inductive component of the motor's winding is drawn and then returned to the source (that is, the EMF) on alternative half cycles of the source voltage. But herein lies the problem. Although the inductive component of the motor's winding doesn't dissipate power, current still moves back and forth between it and the source. In other words, the source current is larger than it really needs to be.

This can be demonstrated by adding some values to Figure 9b as shown in Figure 10 on the next page.

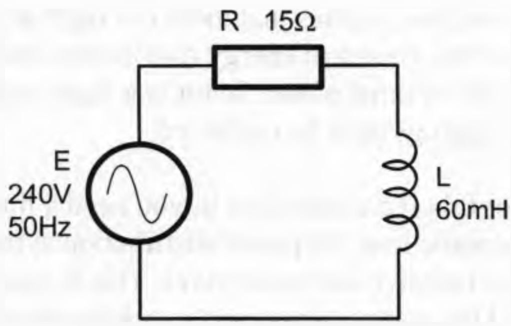


Figure 10 *Figure 9b with values*

Suppose the motor had the same resistance and inductance as the circuit in Figure 8 that you analysed earlier. From the analysis of Figure 8 we know the following:

- The motor winding's inductive reactance (X_L) is: 18.85Ω
- The motor winding's impedance (Z) is: 24Ω
- The motor's current (I) is: 10A RMS
- The motor's real power (P) is: 1500W
- The motor's reactive power is: 1885 vars
- The motor's apparent power (S) is 2400VA
- The power factor is 0.625 lagging

Now, let's consider what would happen if the motor's winding had zero inductance (this is impossible but this is going somewhere). The only power in the circuit would be the real power dissipated by the winding's DC resistance. This would make the real and apparent powers the same at 1500W. Under these conditions, the source current would only be 6.25A instead of 10A (Proof: $I = \frac{P}{V} = \frac{1500W}{240V} = 6.25A$).

The implication of this for power distribution companies is clear. The reactive power of inductive loads requires the distribution infrastructure (that is, the power lines, etc) to handle greater currents than would otherwise be necessary. Moreover, the increased supply currents would also result in greater cable losses in the power distribution system (to understand why, read Appendix 1).

The trouble is, by definition, inductive loads have inductive reactance and this cannot simply be reduced to zero as we theorised about above. However, there is something that can be done.

Recall that inductors and capacitors are opposites in many respects: Their reactances oppose each other and one of them has a current that leads its potential difference while the other has a current that lags it. Importantly, if you compare Figures 4 and 6 closely, you'll notice that they also exchange power with the source at opposite times.

This is so important because, in circuits consisting of a resistor, inductor and capacitor (that is, an RLC circuit), one of the reactive components will be attempting to return power to the source while the other attempts to draw power from it. The upshot is that the capacitor and inductor exchange power between each other. Moreover, if the reactive power (Q) of the capacitor and inductor is the same then there is no exchange of power between them and the source (apart from an initial transfer of power at switch on and switch off).

So, to reduce the source current for an inductive load, a capacitor that requires the same reactive power as the load's inductance should be connected across the load. An example of this is shown in Figure 11.

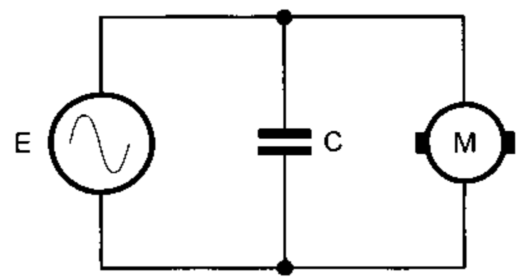


Figure 11 *An inductive load with a shunt capacitor connected to reduce the apparent power*

With this capacitor in place, once it has charged up (requiring a brief extra current from the source at switch-on) the inductor and capacitor exchange reactive power between themselves instead of between the source. This means that the current for the reactive powers of the inductor and capacitor flow between each other freeing the source from having to continuously exchange it.

Electrically, our 1500W motor circuit with an appropriate value of shunt capacitor connected looks like Figure 12 below.

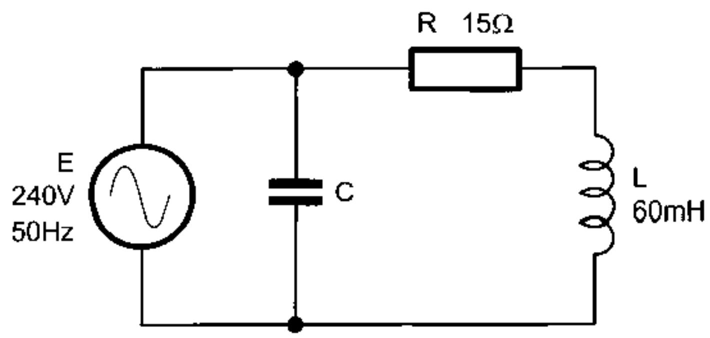


Figure 12 *The 1500W motor from the previous pages with a power factor correction cap connected*

Calculating the value of the capacitor is surprisingly simple (though you'll not be asked to do so in the test). In this example the capacitor must have a reactive power of 1885 vars (to match the motor's inductive power). Knowing this, the capacitor's reactance can be found by transposing the equation $Q = \frac{V_C^2}{X_C}$ to make X_C the subject and solve as follows:

$$X_C = \frac{V_C^2}{Q}$$

$$X_C = \frac{240V^2}{1885\ vars}$$

$$X_C = 30.56\Omega$$

Now, once the capacitor's capacitive reactance is known we can transpose the equation $X_C = \frac{1}{2\pi fC}$ to make C the subject and solve as follows:

$$C = \frac{1}{2\pi fX_C}$$

$$C = \frac{1}{2\pi\times 50Hz\times 30.56\Omega}$$

$$C = 104\mu F$$

Adding a capacitor to inductive loads in this way is known as *power factor correction*. It's so-called because the apparent power goes down to match the real power making the power factor 1. Proof:

$$S = \sqrt{P_R^2 + (Q_C - Q_L)^2}$$

$$S = \sqrt{1500W^2 + (1885\ vars - 1885\ vars)^2}$$

$$S = 1500VA$$

$$pf = \frac{P_R}{S}$$

$$pf = \frac{1500W}{1500VA}$$

$$pf = 1$$

Power factor correction capacitors are usually installed at the switchboard of the industrial complex to correct for all inductive loads therein.

Review questions

Answer these questions to check your understanding of what you have learnt for this chapter. Doing this will also help to prepare you for the tests.

1. *Real* power is dissipated by

   - ☐ resistors only.
   - ☐ capacitors only.
   - ☐ inductors only.
   - ☐ both capacitors and inductors.

2. *Reactive* power is used by

   - ☐ resistors only.
   - ☐ capacitors only.
   - ☐ inductors only.
   - ☐ both capacitors and inductors.

3. What happens to the power transferred to a reactive component when connected to a sinusoidal source?

   - ☐ The power is dissipated as heat.
   - ☐ The power is permanently stored by the component.
   - ☐ The power is returned to the source during another part of the cycle.
   - ☐ Power is never transferred to reactive components so this is a dodgy question.

4. The standard unit of measurement for real power (P) is the

   - ☐ watt (W).
   - ☐ resistive watt (W_R).
   - ☐ volt-ampere reactive (var).
   - ☐ volt-ampere (VA).

5. The standard unit of measurement for reactive power (Q) is the

- ☐ watt (W).
- ☐ resistive watt (W_R).
- ☐ volt-ampere reactive (var).
- ☐ volt-ampere (VA).

6. The standard unit of measurement for apparent power (S) is the

- ☐ watt (W).
- ☐ resistive watt (W_R).
- ☐ volt-ampere reactive (var).
- ☐ volt-ampere (VA).

7. How does the inductor effectively return its power to a sinusoidal source?

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8. How does the capacitor effectively return its power to a sinusoidal source?

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9. Power factor is the ratio of

- ☐ real power to reactive power.
- ☐ real power to apparent power.
- ☐ reactive power to apparent power.
- ☐ apparent power to efficiency.

Re Questions 10 to 12... CII and CIII students will not be tested on power factor correction

10. Power factor correction typically involves connecting

- ☐ an extra inductor across inductive loads.
- ☐ a resistor across inductive and capacitive loads.
- ☐ an extra capacitor across capacitive loads.
- ☐ a capacitor across inductive loads.

11. Power factor correction reduces the circuit's

- ☐ real power.
- ☐ reactive power.
- ☐ apparent power.
- ☐ power factor.

12. Power factor correction is used to

- ☐ reduce the source current without changing the load's real power.
- ☐ increase the source current without changing the load's real power.
- ☐ reduce the source current without changing the load's apparent power.
- ☐ increase the circuit's efficiency.

Questions 13 to 20 refer to the circuit of Figure 1

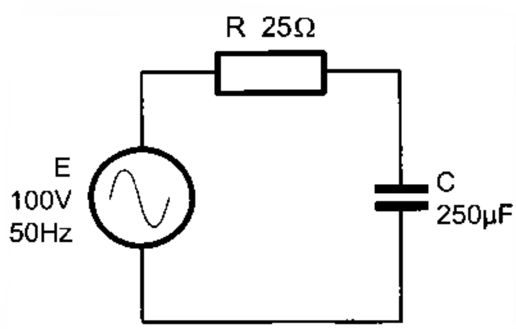

Figure 1

13. Calculate the capacitor's capacitive reactance (X_C).

14. Calculate the circuit's impedance (Z).

15. Calculate the RMS circuit current (I).

16. Calculate the real power dissipated by the circuit (P *or* P_R).

17. Calculate the capacitor's reactive power (Q).

18. Calculate the circuit's apparent power (S).

19. Calculate the circuit's power factor (pf).

20. State whether this power factor is leading or lagging.

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Question 21 refers to the circuit of Figure 2

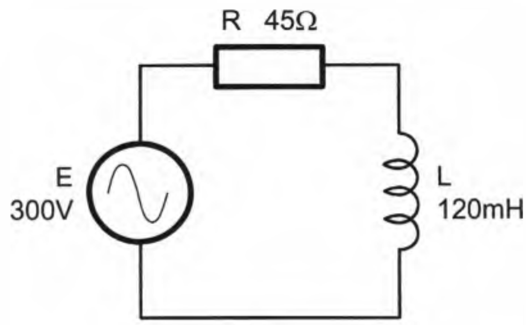

Figure 2

21. The circuit in Figure 2 has a real power (*P*) of 1175W, a reactive power (*Q*) of 984 vars and a power factor of 0.766 lagging. Determine the circuit's apparent power (*S*).

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Student notes

Appendix 1

The advantage of AC over DC for electricity distribution systems

As you probably know, AC power distribution systems are used all over the western world for supplying power to houses, schools, factories, etc. However, this wasn't always the case. The first power distribution systems (circa 1890) supplied DC voltages because most electrical equipment at the time operated on DC. The trouble was, electricity suppliers experienced significant losses over relatively short distances due to the resistance of the transmission cables.

To explain this problem, consider the arrangement in Figure 1 below. It shows a small suburb connected to a power station via a transmission line with 5Ω of resistance.

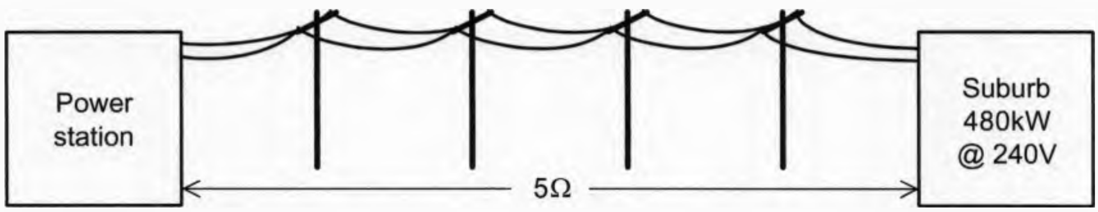


Figure 1 *A DC power distribution system*

Obviously, the power that any suburb "uses" varies from minute-to-minute and hour-to-hour depending on the whether it's day or night, warm or cold and so on. For the purposes of explanation, let's assume that the power used by the suburb at a particular instant is 480kW. At 240V DC, the current in the transmission cable is:

$$P = I \times V$$

$$I = \frac{P}{V}$$

$$I = \frac{480kW}{240V}$$

$$I = 2000A$$

This means that the power dissipated by the cable (called *cable loss*) is:

$$P = I^2 \times R$$

$$P = 2kA^2 \times 5\Omega$$

$$P = 20MW$$

This cable loss has two problems. First, such a high power would likely vaporise the cable! Second, even if there are cables that can dissipate such powers, the power station would be required to generate 20.48MW of power to supply just 480kW to the suburb! The difference (20MW) would be wasted!

Increasing the voltage of the electricity distribution system to 240kV solves this problem (sort of). The current required to provide 480kW at this voltage drops to 2A ($\frac{480kW}{240kV} = 2A$) and so the power dissipated by the cable drops to 20W ($2A^2 \times 5\Omega = 20W$). The cables used for transmission line can easily handle this kind of power level. Moreover, the power needed to be generated by the power station would drop to 480.02kW as there is only a 20W overhead. However, connecting domestic homes and buildings to a supply with such large voltages is ridiculous. People would be electrocuted just standing near their appliances!

Compromises aren't good enough here either. A safe balance between safe voltages and low cable losses can't be achieved. This is where AC systems come in. AC power distribution systems can be designed to generate large AC transmission voltages eliminating the problems associated with cable losses. But, using a transformer, these large voltages can be converted to much safer levels for use in homes etc.

For example, the transformer in Figure 2 below with a turns ratio of 1000 can be used to convert a 240kV transmission voltage to 240V at the suburb as shown in Figure 3 below.

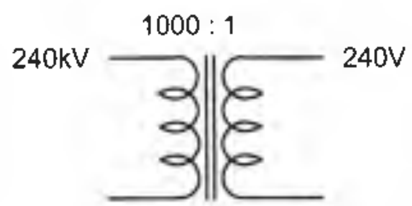


Figure 2 *A transformer with a turns ratio of 1000 converts 240kV to 240V*

Figure 3 *An AC power distribution system to the same suburb as in Figure 1*

This solution gives the best of both worlds. The 240kV transmission line has only 2A flowing through with cable losses of only 20W. And, the suburb is provided with the required amount of power at safer voltage levels.

Typical voltages used for transmission lines include: 11kV, 33kV, 66kV, 110kV, 330kV and 660kV. And, there's a transnational transmission line that operates an 1.2MV.

Appendix 2

The faceplate of two CROs

There are several CROs used here at the electronics department of Sydney Institute. The faceplate of the two CROs you're most likely to use while undertaking this subject are shown here (on the next two pages). The numbers identify controls that are named and explained in Section 3.

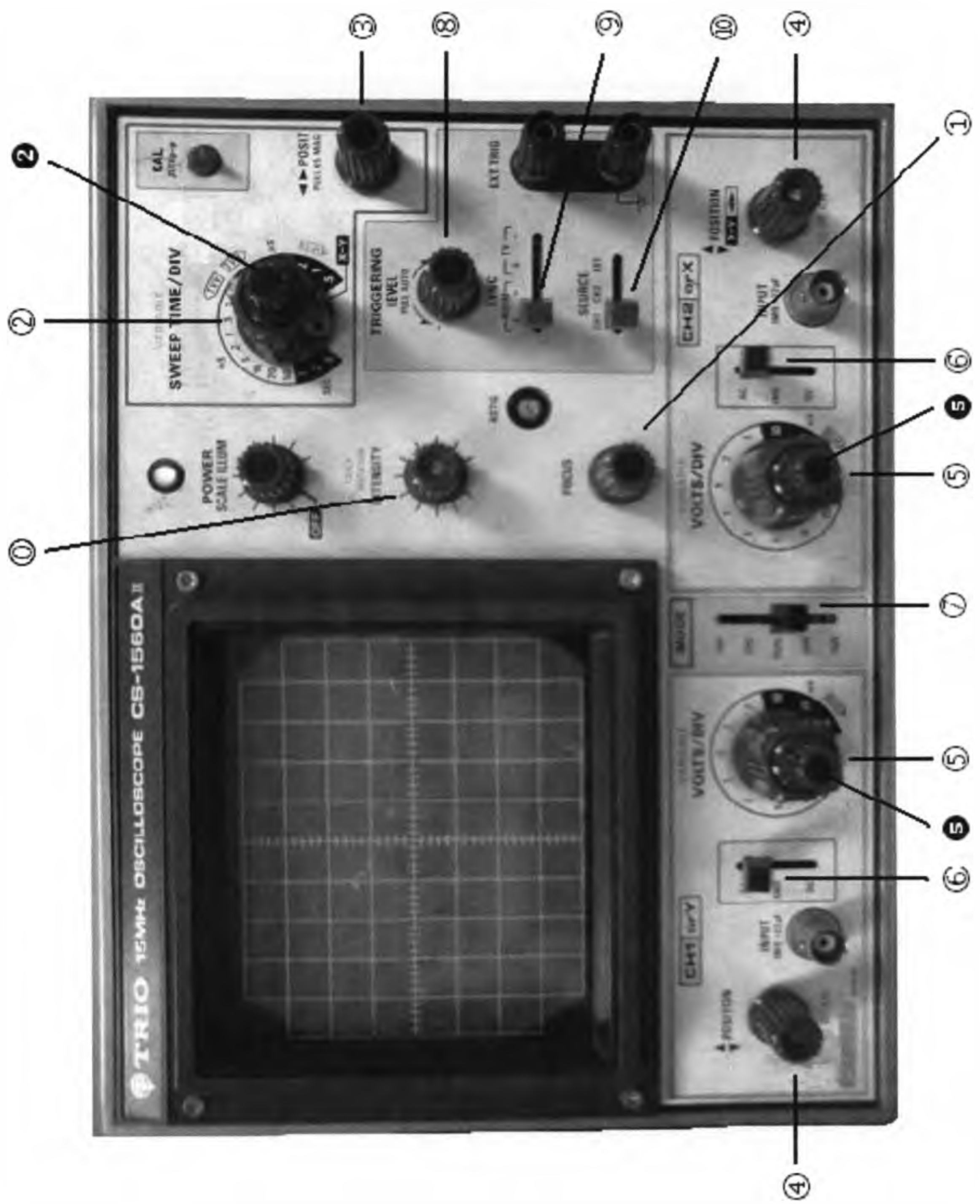


Figure 1 *The faceplate of the TRO 1560A*

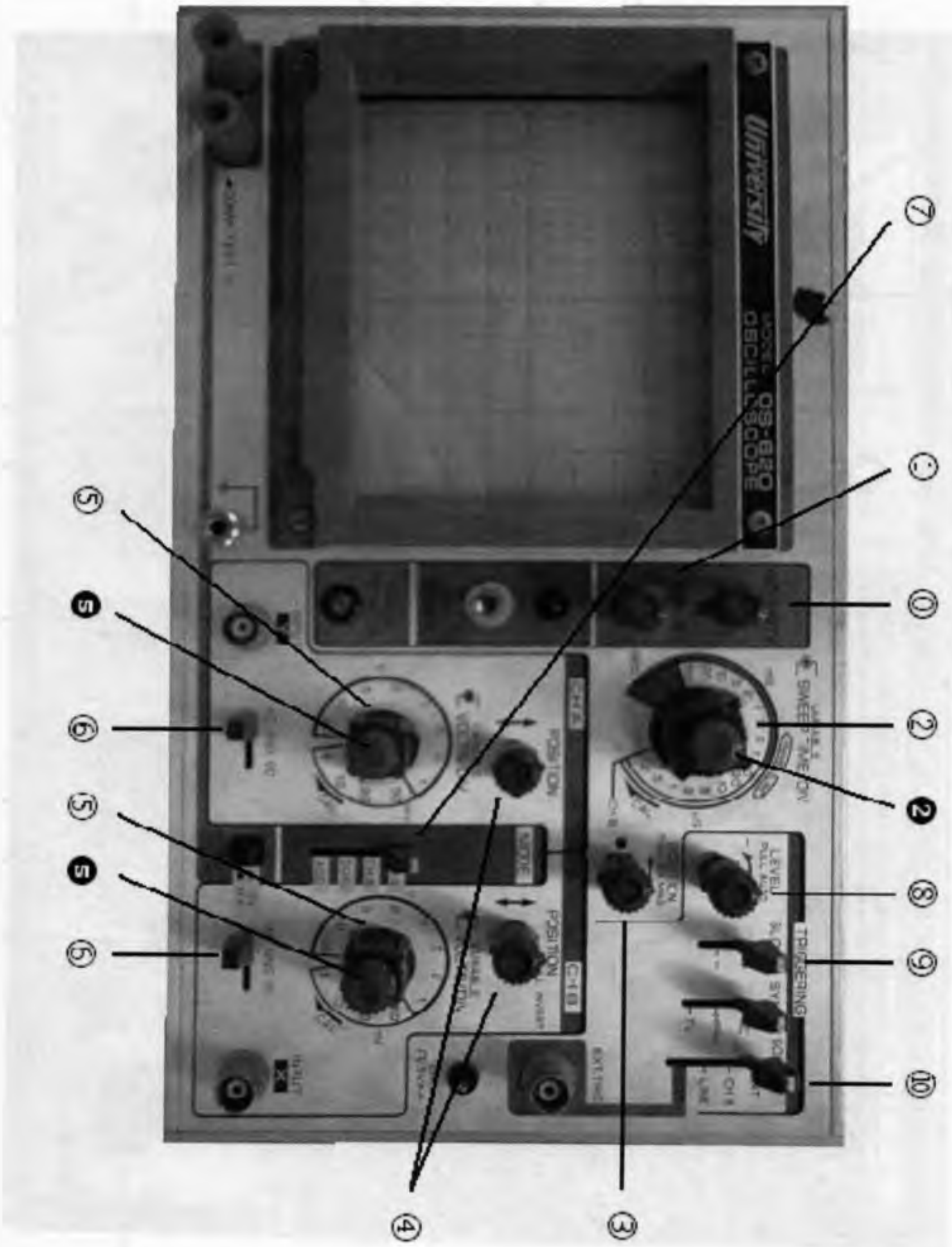


Figure 2 *The faceplate of the University Paton OS-620*

Appendix 3

Section summaries

The theory notes in each Section of this workbook are designed to help you learn about the fundamentals of AC theory. But when you think about it, there's a difference between learning and remembering. These section summaries are designed to help you remember the theory.

Section 1 (9136C - Part 1)

Objectives and Summary

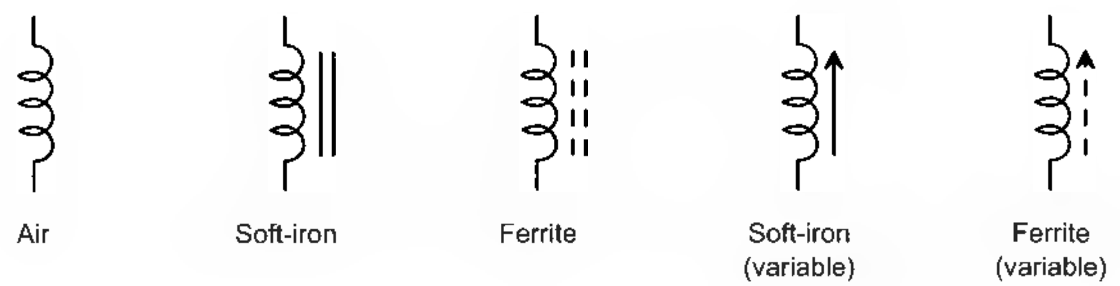
1. Describe the construction of the basic inductor

   An inductor is made of insulated copper wire wound into coils. The centre or "core" may be left unfilled giving an air-core inductor. Alternatively, the wire can be wound around core made from a magnetically conductive material such as soft-iron or ferrite.

2. State other commonly used names for the inductor

   Coil and choke

3. Draw the Australian standard schematic symbols for fixed and variable inductors



4. Explain how the inductor stores energy as an electromagnetic field

   All conductors store energy as a magnetic field because, as current passes through them, a field automatically builds up around. Importantly, when the current is stopped, the field collapses returning energy to the circuit by inducing a current back into the conductor.

   Inductors are better at this than simple conductors because winding the conductor into a coil concentrates the field in a small area.

5. Define inductance and give its symbol

   Inductance is the opposition to changes in current through a conductor. It's symbol is L.

6. State the unit of measurement for inductance and give its symbol

   Inductance is measured in Henries (H).

7. List the factors that affect the inductance of an inductor

   (1) The number of windings; (2) the permeability of the core; (3) the length of the coil; and (4) the cross-sectional area of the windings.

   You should also know that inductance is proportional to the number of windings (in a square-law function), it's directly proportional to pemeability and area, and it's indirectly proportional to length.

8. Calculate the value of an inductor given its physical dimensions and the permeability of the core

   The equation for this is: $L = \frac{N^2 \times a \times \mu}{l}$

9. List typical applications for inductors in electronic circuits

   To name just a few... Inductors can be used as an energy reservoir like capacitors. They can be used to protect electronics equipment from *surges* on mains. They can also be used together with capacitors to make filters and oscillators for communications equipment. They can be used as sensors (an example is the inductive loop embedded in the road at traffic lights to detect when a car is waiting).

10. List examples of where the inductive effect occurs unintentionally

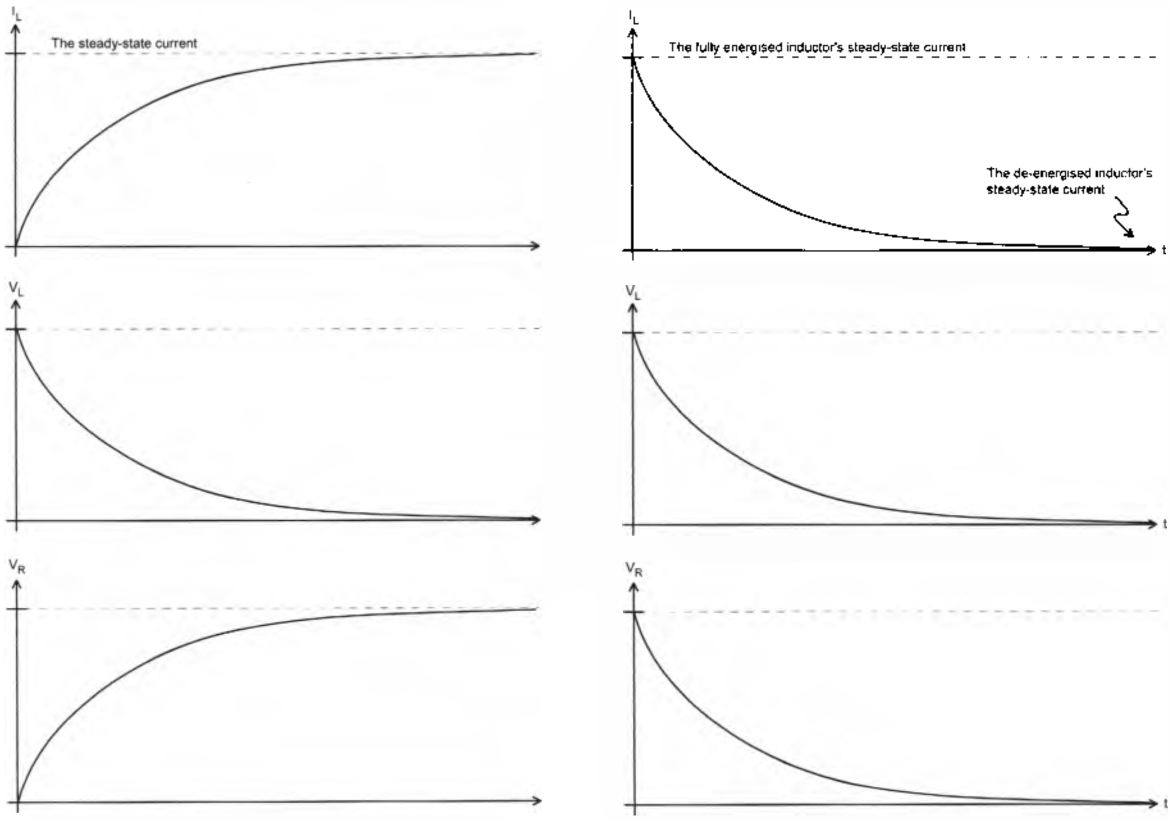
    PCB tracks and cables used to join circuit boards.

11. Recognise common commercially available inductors

    You'll use inductors throughout this subject and will get to see many different types. Also, ask the technicians at work to show you examples of inductors in the equipment they repair.

12. Draw the graph of the energising and de-energising characteristic for an inductor in single-source DC series RL circuits

Energising curves De-energising curves



13. Calculate the time constant of series RL circuits

$$\tau = \frac{L}{R}$$

14. Calculate the total time it takes to energise and de-energise an inductor in a single-source DC series RL circuit

Energise/de-energise time = $5 \times \tau$

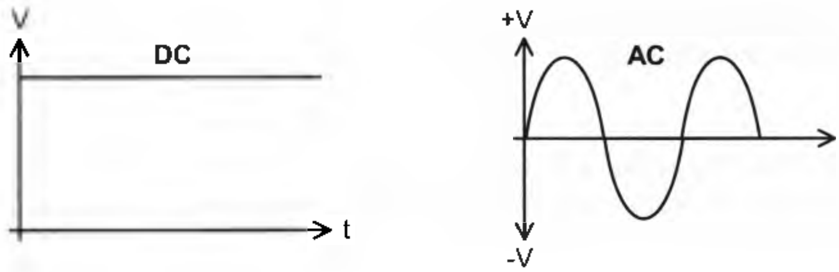
Section 2 (9136C - Part 1)

Objectives and Summary

1. Explain the difference between alternating current (AC) and direct current (DC).

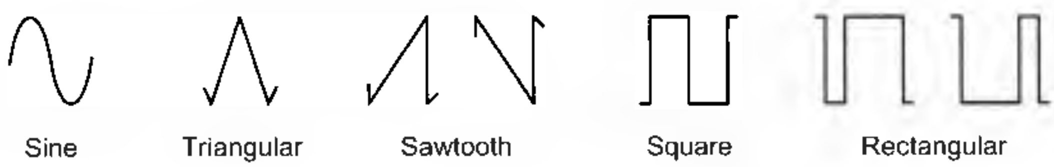
   DC voltages and currents don't change over time. AC voltages and currents reverse polarity at fixed intervals.

   Eg.



2. Recognise AC waveforms including symmetrical and non-symmetrical sinewaves, squarewaves and triangular waves.

   AC waveforms include:

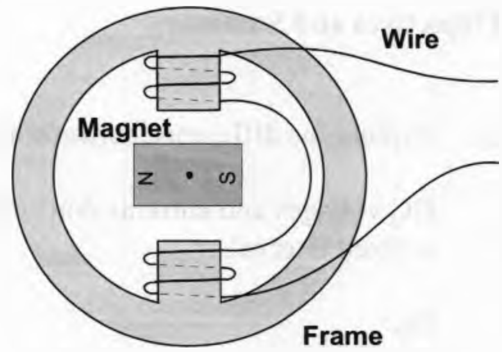


3. Explain the advantage of using AC voltages for power distribution over DC voltages.

   AC voltages can be transformed to higher and lower voltages much more easily than DC voltages allowing them to be transmitted over long power line with fewer losses.

4. Explain how a sinewave is generated.

In the set-up shown on the right, the magnet is made to spin. This causes a magnetic flux to flow through the frame that continuously changes. Starting from zero, the flux rises to maximum in one direction, falls back to zero then onto maximum again but in the opposite direction through the frame then finally back to zero to start again.



This continuously changing magnetic field induces a current in the wire wrapped around the frame that is sinusoidal.

5. Define the following terms with regard to sinewaves: *period*, *frequency*, *peak value*, *peak-to-peak value*, *instantaneous value* and *RMS value*.

Period: The duration in seconds of complete one cycle of an AC waveform.

Frequency: The number of cycles of an AC waveform in one second.

Peak value: The voltage of an AC waveform measured from the centre of the waveform to either the highest point (the positive peak) or the lowest point (the negative peak).

Peak-to-peak value: The voltage of an AC waveform measured from the positive peak to the negative peak.

Instantaneous value: The voltage of an AC waveform at any point in the cycle (this means that there are an infinite number of instantaneous voltages for an sinewave).

RMS value: RMS stands for the root, mean square value of an AC waveform. In practice, the RMS value is the equivalent amount of DC voltage/current needed to cause wire or a component to heat up by the same amount as the AC voltage.

6. Calculate either the peak value, peak-to-peak value, instantaneous value or the RMS value of a sinewave voltage or current given one of the other values.

   Use the review questions to practise this. The equations are:

Peak values:	$v_P = \frac{v_{P-P}}{2}$	and	$i_P = \frac{i_{P-P}}{2}$
also:	$v_P = 1.414 \times v_{RMS}$	and	$i_P = 1.414 \times i_{RMS}$
Peak-to-peak values:	$v_{P-P} = v_P \times 2$	and	$i_{P-P} = i_P \times 2$
Instantaneous values:	$v = v_P \times Sin\theta$	and	$i = i_P \times Sin\theta$
RMS values:	$v = 0.707 \times v_P$	and	$i = 0.707 \times i_P$

7. State the unit of measurement for *frequency*

   Frequency is measured in Hertz (Hz)

8. Calculate either the frequency or period of a sinewave given the other.

   Use the review questions to practise this. The equations are:

   Frequency: $f = \frac{1}{P}$

   Period: $P = \frac{1}{f}$

9. List the properties of AC signals that can be measured using multimeters.

   AC meters measure the RMS value of the voltage or current. [More expensive meters can sometimes measure the peak value and frequency.]

10. List the advantages and disadvantages of measuring AC signals with multimeters.

Advantages

- Easy to use
- Measures RMS so no conversions needed to calculate power values

Disadvantages

- Can't see the waveform
- Measures RMS so if other values are needed they must be calculated
- Can only measure the voltage/current of waveforms up to a couple of kilohertz
- Unless the meter is a *true RMS* meter, they can only be used for sinewaves
- Unless the meter is a more expensive model, you can't measure frequency or period

Section 3 (9136C - Part 1)

Objectives and Summary

1. List the advantages of using an oscilloscope over a multimeter to measure AC voltages

   Advantages include: You can see the signal's shape (which is good when the problem with the equipment is due to distortion); you can measure the peak and peak-to-peak voltages of the signal; you can measure the signal's period (from which you can calculate its frequency).

2. Describe the basic operation of an oscilloscope

   The cathode ray tube (CRT) "fires" and electron beam from the back of the tube towards the front. When the electrons hit the inside front of the screen, their kinetic energy is converted to light producing a dot on the screen.

   Even without an input signal connected, the CRO is designed to move the dot from left to right. When the dot gets to the right-side of the screen it instantly jumps back to the left side to start another sweep across the screen. If this is done quick enough, the moving dot creates a line on the screen which is called a trace.

   Connecting a signal to one of the CRO's inputs causing the dot to go up and down at the same rate as the signal. The combination of the dot moving left to right and up and down produces a copy of the signal on the screen.

3. Explain the purpose of commonly used oscilloscope controls

Intensity ⓪	Adjusting the *Intensity* varies the brightness of the trace on the CRO's screen.
Focus ①	Adjusting the *Focus* varies the sharpness of the trace on the CRO's screen.
Horizontal sweep or **Sweep time/division control** or **Timebase** ②	The *Horizontal Sweep* control adjusts the speed of the electron beam as it moves from left to right across the screen.

Variable horizontal sweep
❷

This is the red (or blue) knob inside the *Horizontal Sweep* control. For normal use of CROs this control should be in the "detent" (locked) position.

When the *Variable Horizontal Sweep* control is engaged (usually by turning it anti-clockwise out of the detent position) the sweep rate can be changed to rates other than those specified around the *Horizontal Sweep* knob.

Horizontal position
③

Turning this control anti-clockwise moves the whole trace to the left of the screen. Turning this control clockwise moves the whole trace to the right.

Horizontal magnification
or
×5 mag control
③

The *Horizontal Magnification* control is usually engaged by pulling the *Horizontal Position* knob out. It instantly increases the sweep rate by a factor of 5 (or 10 depending on the CRO). This means that you must divide the horizontal sweep setting by 5 (or 10) when calculating the period.

Vertical position
④

Turning this control anti-clockwise moves the trace up the screen. Turning this control clockwise moves the trace down the screen.

Vertical attenuation
⑤

If an input signal is too large, the top and bottom of it will not fit on the screen (that is, the vertical deflection is too great). The *Vertical Attenuation* reduces the input signal's size so that it can fit on the screen.

There are two *Vertical Attenuation* controls, one for each channel (or input). The settings around the knob tell you what each whole vertical division on the graticule represents as a voltage.

Variable vertical attenuation
❺

This is the red (or blue) knob inside the *Vertical Attenuation* control. For normal use of CROs this control should be in the "detent" (locked) position.

When the *Variable Vertical Attenuation* control is engaged (usually by turning it anti-clockwise out of the detent position) the attenuation of the input signal can be changed to levels other than that specified around the *Vertical Attenuation* knob.

Input coupling
⑥

There are two *Input Coupling* controls, one for each channel. They have three settings: *AC*, *GND* and *DC*. When set to the *GND* position the input signal is disconnected from the CRO (internally). Instead, the input to the CRO is connected directly to ground. This helps you to find the zero position on the screen.

When the *Input Coupling* is set to the *DC* position, the input signal is directly connected to the CRO and so the trace responds to all input signals (both AC and DC).

When the *Input Coupling* is set to the *AC* position, the input signal is connected to the CRO via a capacitor. This means that the trace only moves up or down in response to AC signals. DC signals are ignored because capacitors block DC.

Mode
⑦

This control allows the user to view the channel 1 input on its own, the channel 2 input on its own or both inputs at the same time. Viewing both inputs at the same time is used to compare signals.

Auto-triggering
⑧

Auto triggering is usually engaged by pulling out the *Trigger Level* knob. This ensures that there is a trace on the screen if the *Trigger Level* is not set correctly or even if there is no input signal.

Triggering level
⑧

Adjusting the *Triggering Level* control varies the point on the input signal where the trace starts its sweep across the screen. Care must be taken not to turn this control too much left or right otherwise the trace becomes unstable.

Trigger synchronisation
or
Sync
or
Slope
⑨

The *Sync* control is part of the triggering circuitry. For normal operation, it should be switched to either the "+" or "-" setting and determines whether the trace starts on the input signal's rising or falling edge.

The control has two other settings that can be used when looking at signals in television circuits.

Trigger source
or
Source
⑩

The *Trigger Source* control is also part of the triggering circuitry. For normal operation, it should be switched to the setting that matches the channel that you're input signal is connected to.

4. Set up an oscilloscope in readiness to make DC or AC voltage measurements

   See the procedure on pages 3-6 and 3-7. You're encouraged to practice this procedure at the beginning of every skill practice exercise.

5. Measure the amplitude and duration (ie the period) of AC waveforms

   You're given an opportunity to practice these skills in the practical parts of almost every lesson.

6. Measure the size of DC voltages

   Ditto.

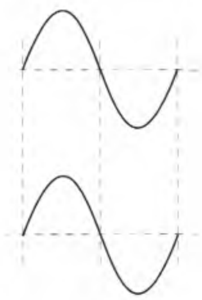
Section 4 (9136C - Part 1)

Objectives and Summary

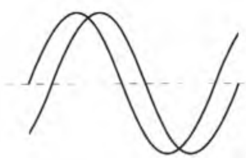
1. Define the terms *phase angle*, *in phase*, *out of phase*, *phase difference* and *phase shift* as applied to AC signals

   Phase angle: The position of an instantaneous voltage or current (specified in degrees between 0° and 360°).

   In phase:



   Out of phase:



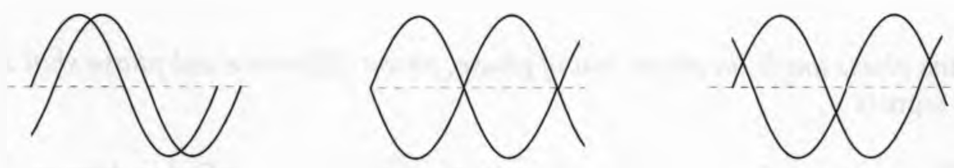
   Phase difference: The amount that two (or more) AC waveforms are out of phase. One is said to lead or lag the other.

   Phase shift: A phase shift is said to occur when the input and output signals to a circuit are out of phase.

2. State the unit of measurement for phase difference

   The degree (eg 90°)

3. Draw examples of two or more sinewaves that are out of phase by less than, more than and exactly 180°



<180° 180° >180°

4. Measure the phase difference between two sinewaves using an oscilloscope

   You're given an opportunity to practice these skills in the practical parts of several lessons.

5. Define the term *phasor*

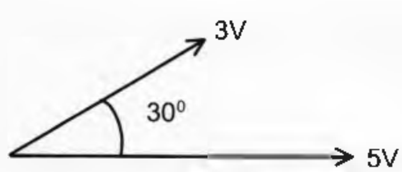
   A phasor is just a straight line that represents an individual sinewave. Voltage phasors have open-ended arrow heads and current phasors have closed-ended arrow heads. Phasors only use peak voltages or currents.

6. Draw the phasor diagram for two or more sinewaves that are in phase and out of phase with each other

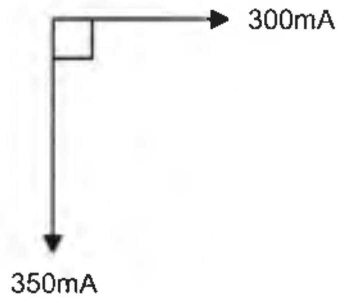
   Use the review questions to practise this skill. Examples are shown below:

A $50V_{pk}$ sinewave.

A $2A_{pk}$ sinewave.

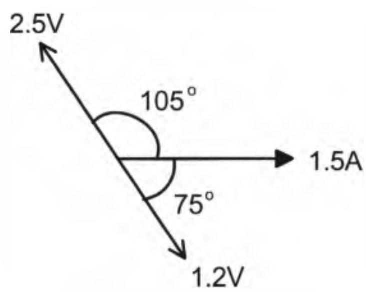


A $5V_{pk}$ reference sinewave with a $3V_{pk}$ sinewave leading it by 30°.



A 300mA$_{pk}$ reference sinewave with a 350mA$_{pk}$ sinewave lagging it by 90°.

A 38mA$_{pk}$ sinewave in phase with an 85mV$_{pk}$ sinewave.



A 1.5A$_{pk}$ reference sinewave with a 2.5V$_{pk}$ sinewave leading it by 105° and a 1.2V$_{pk}$ sinewave lagging it by 75°.

7. Explain the advantages of representing sinewaves using phasors

   They're better than looking at sinewaves when considering the phase relationship between three or more of them.

Section 5 (9136C - Part 1)

Objectives and Summary

1. Explain the basic operation of the ideal transformer

   Two coils of insulated wire are placed next to each other. An AC source is connected to one of them which causes a continuously expanding/collapsing electromagnetic field about it. As the second coil is physically close to the first, the electromagnetic energy produces an AC potential difference across it (even though it's not electrically connected to anything) due to mutual inductance.

2. Explain the difference between the ideal and practical transformer

   Ideal transformers transfer all of the energy from one winding to the other. In practice though, mains transformers transfer about 98% of the energy. Other types of transformers transfer much less (in fact, some are designed to transfer as little as 5% of it).

3. Define the terms *primary winding*, *primary voltage*, *primary current*, *secondary winding*, *secondary voltage* and *secondary current* as applied to transformers

   The primary winding is the winding that the AC source is connected to (ie the input).

   The primary voltage is the potential difference across this winding and the primary current is the current flowing through it.

   The secondary winding is the winding that the energy is transferred to (ie the output).

   The secondary voltage is the potential difference across this winding and the secondary current is the current flowing through it.

4. Define the terms *one-to-one*, *step-up* and *step-down* as applied to transformers

   A one-to-one transformer has the same primary and secondary voltages.

   A step-up transformer has a bigger secondary voltage than the primary.

   A step-down transformer has a smaller secondary voltage than the primary.

5. Define the terms *turns ratio*, *voltage ratio*, *current ratio* and *power ratio* as applied to transformers

   These ratios are just a numerical comparison of the primary and secondary's turns/voltages/currents/powers.

6. Calculate the turns ratio, voltage ratio, current ratio and power ratio of a transformer

   Use the review questions to practise this. The equations are:

   $N = \frac{N_P}{N_S}$

   $Voltage\ ratio = \frac{V_P}{V_S}$

   $Current\ ratio = \frac{i_P}{i_S}$

   $Power\ ratio = \frac{P_P}{P_S}$

7. Calculate either the primary voltage, secondary voltage or turns ratio given values for the others

   Use the review questions to practise this. The equation is:

   $N = \frac{V_P}{V_S}$

8. Calculate the primary current given the primary voltage, the turns ratio and the load resistance

   Use the review questions to practise this. The equations are:

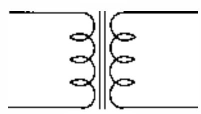
   $i_S = \frac{v_S}{R}$

   $P_S = i_S \times v_S$

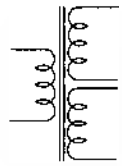
   $P_S = P_S$ (for mains transformers)

   $i_P = \frac{P}{v_P}$

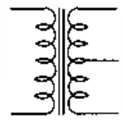
9. Draw the schematic symbol for commonly used transformers in electronic circuits



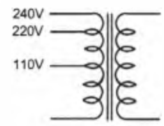
Simple
mains xformer



Dual
secondary

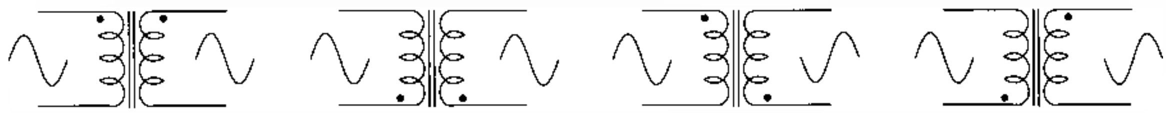


Centre-tapped



Tapped
primary

10. Predict the phase relationship between the input and output of transformers using *dot convention*



Section 6 (9136C - Part 1)

Objectives and Summary

1. Calculate either the current, voltage or resistance of a single resistor circuit given a value for the other two (where the voltage and current can be specified using either peak, peak-to-peak, RMS or instantaneous values)

   Use the review questions to practise this. The equation is:

   $$I_{Rn} = \frac{V_{Rn}}{Rn}$$

   Note: This equation is not on the equation sheet that you'll be given in the tests.

2. Calculate either the circuit current, supply voltage or total resistance of a series, parallel or series-parallel resistive circuit given a value for the other two (where the voltage and current can be specified using either peak, peak-to-peak, RMS or instantaneous values)

   Use the review questions to practise this. The equations are:

   $$I_T = \frac{E}{R_T}$$

   $$R_T = R_1 + R_2 + R_n$$

   $$R_T = \frac{1}{\frac{1}{R1} + \frac{1}{R2} + \frac{1}{Rn}}$$

   Note: These equations are not on the equation sheet that you'll be given in the tests.

3. Calculate potential differences and branch currents around series, parallel and series-parallel resistive circuits given either the supply voltage or total circuit current (where the voltages and currents can be specified using either peak, peak-to-peak, RMS or instantaneous values)

   Use the review questions to practise this. The equation is:

   $$I_{Rn} = \frac{V_{Rn}}{Rn}$$

   Note: This equation is not on the equation sheet that you'll be given in the tests.

4. Calculate a potential difference or branch current using Kirchhoff's voltage and current laws

   Use the review questions to practise this. The equations are:

   $E = V_{R1} + V_{R2} + V_{Rn}$

   $I_T = I_{R1} + I_{R2} + I_{Rn}$

   Note: These equations are not on the equation sheet that you'll be given in the tests.

5. State the phase relationship between voltage and current in purely resistive circuits

   The potential difference across a resistor and the current through it are always in phase.

Section 7 (9136C - Part 1)

Objectives and Summary

1. Explain why voltage and current in a purely inductive circuit are out of phase

   When the current through an (ideal) inductor is maximum, its resistance to changes in current must be minimum. So the potential difference across it must be minimum also.

2. State the phase relationship between voltage and current in a purely inductive circuit

   The potential difference across an (ideal) inductor always leads the current through it by 90°.

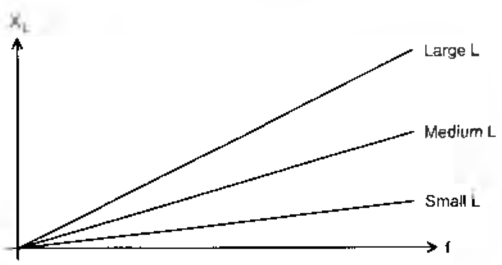
3. Define the term *inductive reactance*

   Inductive reactance is the inductor's resistance to changes in current.

4. State the symbol and unit of measurement for inductive reactance

   The symbol for inductive reactance is: X_L. It's measured in Ohms: Ω.

5. Draw the graph of frequency versus inductive reactance



6. Calculate either the inductive reactance, inductance or frequency in an inductive circuit given values for the other two

   Use the review questions to practise this. The equation is:

   $X_L = 2\pi fL$

7. Explain why voltage and current in a purely capacitive circuit are out of phase

   When the potential difference across a capacitor is maximum, its resistance to changes in voltage must be maximum. So the circuit current must be minimum.

8. State the phase relationship between voltage and current in a purely capacitive circuit

   The potential difference across a capacitor always lags the circuit current by 90°.

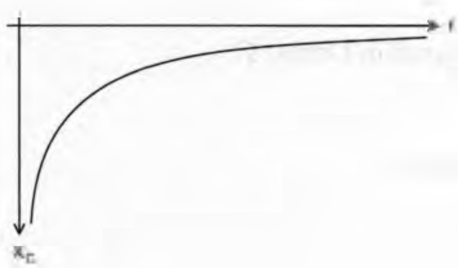
9. Define the term *capacitive reactance*

   Capacitive reactance is the capacitor's resistance to changes in potential difference.

10. State the symbol and unit of measurement for capacitive reactance

    The symbol for capacitive reactance is: X_C. It's measured in Ohms: Ω.

11. Draw the graph of frequency versus capacitive reactance



12. Calculate either the capacitive reactance, capacitance or frequency in a capacitive circuit given values for the other two

    Use the review questions to practise this. The equation is:

    $X_C = \frac{1}{2\pi fC}$

Section 8 (9136C - Part 1)

Objectives and Summary

1. Define the term *impedance*

   Impedance is the combined resistive effect of all resistance and reactance in a circuit. Importantly, it's <u>not</u> the <u>sum</u> of them.

2. State the symbol and unit of measurement for impedance

   The symbol for impedance is: *Z*. It's measured in Ohms: Ω.

3. Simplify series RL, RC and RLC circuits to a single equivalent impedance

   Use the review questions to practise this. The equations are:

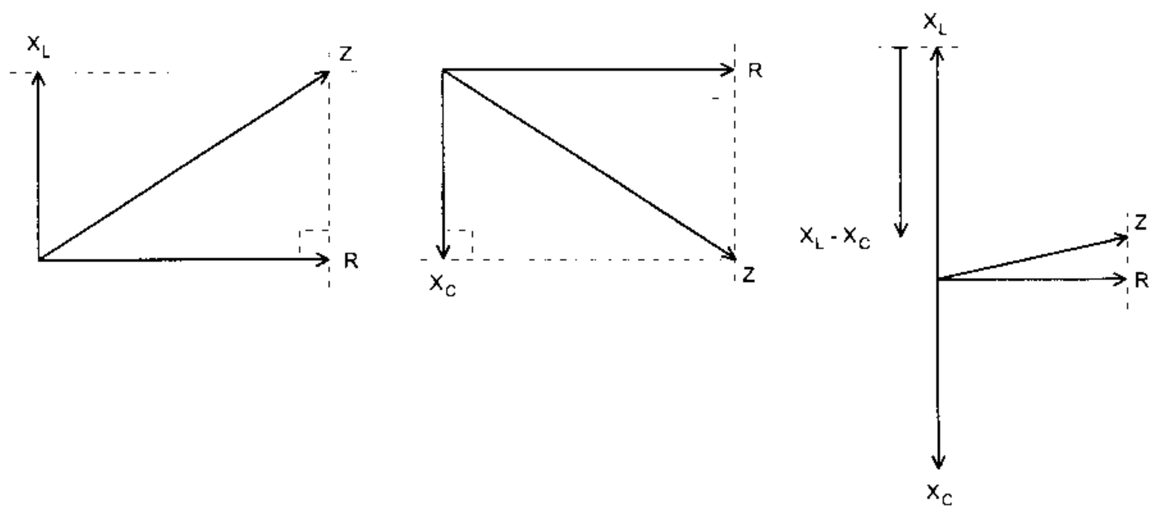
   $$Z = \sqrt{R^2 + X_L^2}$$

   $$Z = \sqrt{R^2 + X_C^2}$$

   $$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

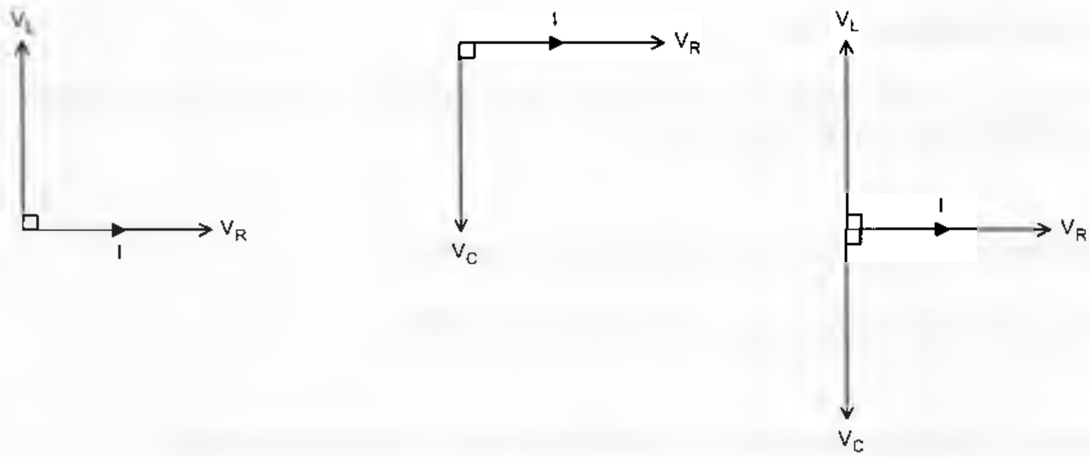
4. Draw the vector diagram showing the relationship between resistance and reactance for series RL, RC and RLC circuits

   Examples include:



5. Draw the phasor diagram showing the current and all voltages in series RL, RC and RLC circuits

   Examples include:



6. Describe the relationship between frequency and the magnitude and angle of impedance in series RL, RC and RLC circuits

   As frequency increases in RL circuits, the angle of the impedance relative to the resistance increases from 0° toward +90°.

   As frequency increases in RC circuits, the angle of the impedance relative to the resistance increases from -90° toward 0°.

   As frequency increases in RLC circuits, the angle of the impedance relative to the resistance increases from -90° through to 0° then on toward +90°.

Section 9 (9136C - Part 1)

Objectives and Summary

1. Calculate either the current, voltage or impedance of a series RL or RC circuit given a value for the other two (where the voltage and current can be specified using either peak, peak-to-peak, RMS or instantaneous values)

   Use the review questions to practise this. The equation is:

   $I_T = \frac{E}{Z}$

2. Calculate potential differences across components of known value in series RL or RC circuits given either the supply voltage or circuit current (where the voltages and currents can be specified using either peak, peak-to-peak, RMS or instantaneous values)

   Use the review questions to practise this. The equations are:

   $V_R = I \times R$

   $V_C = I \times X_C$

   $V_L = I \times X_L$

3. Describe the *resonance* effect in terms of the impedance in series RLC circuits

   Resonance occurs when the circuit impedance is the same as the circuit's total resistance.

4. State the relationship between inductive and capacitive reactance at resonance in series RLC circuits

   Inductive and capacitive reactance are equal in magnitude. However, as they're opposite in direction, they cancel each other out completely

Section 10 (9136C - Part 1)

Objectives and Summary

1. Define the terms *real power*, *reactive power* and *apparent power*

   Real power is the only power dissipated in RL, RC and RLC circuits. It's dissipated by the resistors in the circuit.

   Reactive power is power that looks like it is dissipated by inductors and capacitors in RL, RC and RLC circuits. However, the power is effectively returned to the supply over the cycle.

   Apparent power is the mathematical combination of the real and reactive powers. Importantly, it's not the simple sum of them.

2. State the symbol for the above and their unit of measurement

   Real power is P_R and is measured in Watts (W).

   Reactive power is Q and is measured in volt-amps reactive (vars).

   Apparent power is S and is measured in volt-amps (VA)

3. Explain why (ideal) inductors and capacitors don't dissipate power when connected to a sinusoidal source

   Circuit conditions allow the energy stored in the inductor/capacitor to be returned to the circuit and dissipated by the resistor. During this time, the supply is relieved of having to provide power to the resistor so it is said that the power is effectively returned to the supply.

4. Calculate the real, reactive and apparent powers in an RL, RC or RLC circuit given the EMF voltage, EMF frequency and component values

   Use the review questions to practise this. The equations are:

$$P_R = I \times V_R \qquad P_R = \frac{V_R^2}{R} \qquad P_R = I^2 \times R$$

$$Q = I \times V_L \qquad Q = \frac{V_L^2}{X_L} \qquad Q = I^2 X_L$$

$$Q = I \times V_C \qquad Q = \frac{V_C^2}{X_C} \qquad Q = I^2 \times X_C$$

$$S = I_T \times E \qquad S = \frac{E^2}{Z} \qquad S = I_T^2 \times Z \qquad S = \sqrt{P_R^2 + Q^2}$$

5. Explain the term *power factor*

   Power factor is a numerical comparison of the real to apparent powers.

6. Calculate the power factor of an RL or RC circuit given the EMF voltage, EMF frequency and component values

   Use the review questions to practise this. The equation is:

   $pf = \frac{P_R}{S}$

Answers to review questions

Section 1

1. initially opposes the flow of current.

2. whenever the current flowing through a conductor changes.

3. Henries

4. only as the field expands or contracts.

5. develops an electromagnetic field.

6. All of the above

7. decreases its inductance.

8. increases its inductance.

9. doesn't have an affect on its inductance.

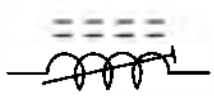
10. increases its inductance.

11. has a small but insignificant affect on its inductance.

12. Fixed value soft iron core inductor

13. None of the above

14.



15. Number of turns
    Permeability of the core
    Cross-sectional area of the core
    Length of the inductor

16. Tuning for radio and television sets
    Transformers

17. Measure the resistance of the inductor. If it is open-circuit then the inductor is definitely damaged. A very low resistance reading may indicate that it is damaged also (though not necessarily).

Section 1 (continued)

18. The time constant is the time it would have taken the circuit current to reach maximum if it increased at a constant rate equal to the initial rate of increase instead of slowing down.

19. Inversely proportional. That is, the greater the resistance, the shorter the time constant.

20. $\tau = \frac{L}{R}$

$\tau = \frac{330mH}{680\Omega}$

$\tau = 485\mu s$

21. Total time $= 5 \times \tau$

$= 5 \times 485\mu s$

$= 2.425ms$

22. If the inductor is ideal then it has no resistance. Therefore…

$I = \frac{E}{R}$

$I = \frac{5V}{680\Omega}$

$I = 7.35mA$

23. The same amount of time that it took to reach maximum which was 2.425ms

24. It would remain the same

Section 1 (continued)

25. $\tau = \frac{L}{R_T}$

$\tau = \frac{10mH}{27k\Omega + 12k\Omega}$

$\tau = 256ns$

Total time $= 5 \times \tau$

$= 5 \times 256ns$

$= 1.28\mu s$

26. $\tau = \frac{L}{R2}$

$\tau = \frac{10mH}{12k\Omega}$

$\tau = 833ns$

Total time $= 5 \times \tau$

$= 5 \times 833nS$

$= 4.17\mu s$

Section 2

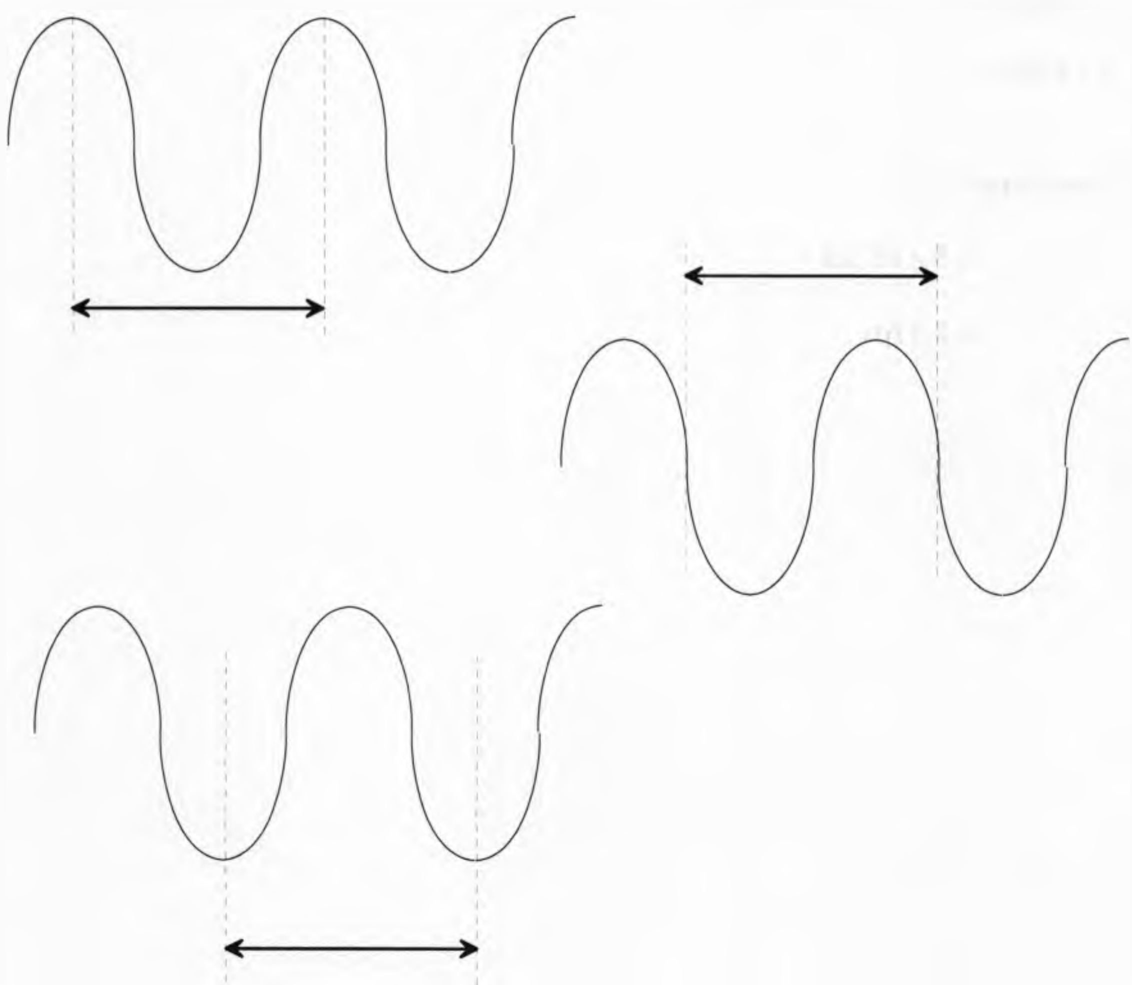
1. reverse direction.

   Note: it might be tempting to say that the first answer "are constantly changing" is also correct (or even more so), however, it's not. A true AC waveform must have voltage/current polarity that reverses. Also, there are AC waveforms like square waves that have current that reverses but is not constantly changing.

2. (a) Sinewave
   (b) Triangular wave
   (c) Square wave

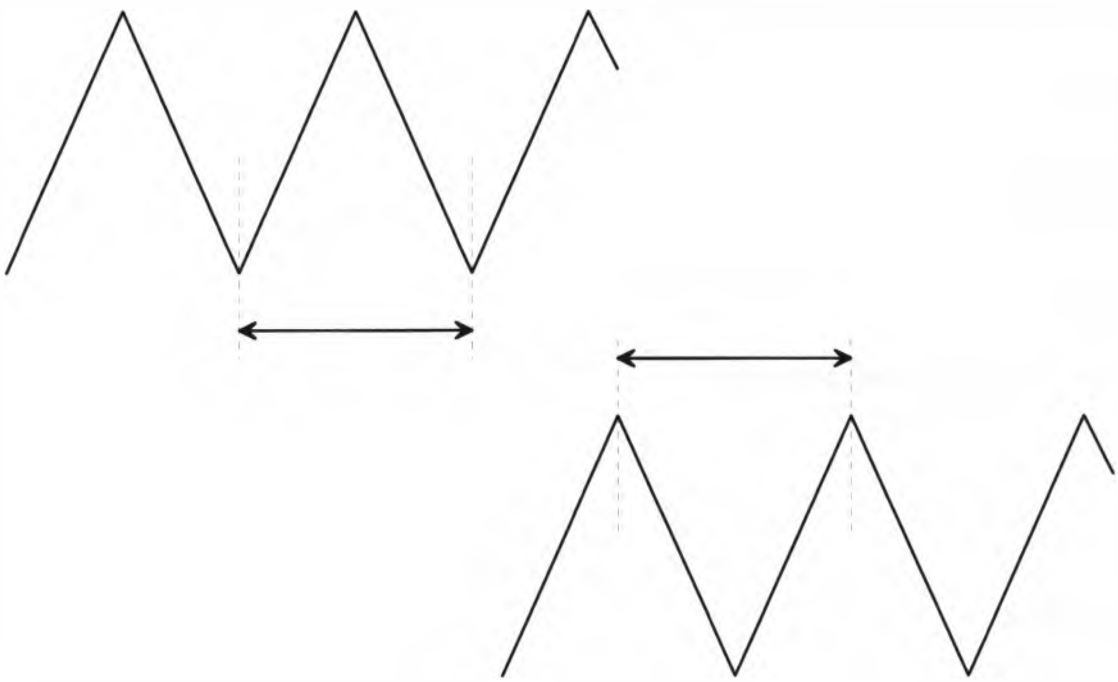
3. Cycle

4. (a) This could have been answered in several ways. See below for examples.

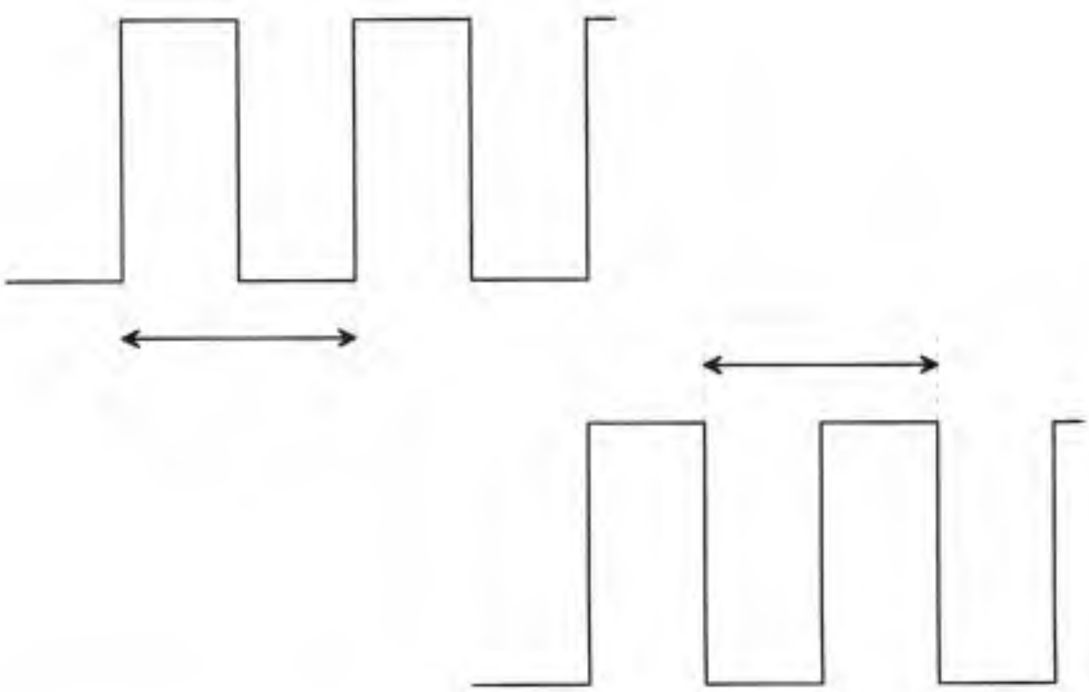


Section 2 (continued)

(b)



(c)



Section 2 (continued)

5. Seconds

6. the time it takes to complete one cycle.

7. 360°

8. (a) 2μs
   (b) 10ms
   (c) 0.7s

9. Hertz

10. the number of cycles per second.

11. $f = \frac{1}{P}$

$f = \frac{1}{50s}$

$f = 20kHz$

12. $P = \frac{1}{f}$

$P = \frac{1}{250Hz}$

$P = 4ms$

13. As the period of a 15kHz sinewave is 66.67μs, the number of complete cycles in 1.5ms is found by:

$\frac{1.5ms}{66.67\mu s} = 22.5$

So the answer is 22 complete cycles.

14. Peak-to-peak

15. Peak

16. Amplitude

17. RMS value.

All values are considered to be RMS unless otherwise stated.

Section 2 (continued)

18. The RMS value of an AC voltage is the DC voltage that would be needed produce the same heating effect.

19.

(a)

$V_{pk} = \frac{V_{p\text{-}p}}{2}$

$V_{pk} = \frac{420V_{p\text{-}p}}{2}$

$V_{pk} = 210V_{pk}$

(b)

$V_{RMS} = 0.707 \times V_{pk}$

$V_{RMS} = 0.707 \times 210V_{pk}$

$V_{RMS} = 148.5V_{RMS}$

20.

(a)

$V_{pk} = \frac{1}{0.707} \times V_{RMS}$

$V_{pk} = 1.414 \times 150V_{RMS}$

$V_{pk} = 212.1V_{pk}$

(b)

$V_{p-p} = 2 \times V_{pk}$

$V_{p-p} = 2 \times 212.1V_{pk}$

$V_{p-p} = 424.2V_{p-p}$

Section 2 (continued)

21.

(a)

$v = V_{pk} \times Sin\theta$

$v = 42.5V_{pk} \times Sin45^o$

$v = 30V$

(b) 42.5V

(c) 24.38V

(d) -36.8V

22. The period of a 2kHz sinewave is 500µs. The question is asking what would be the voltage after only 200µs of the cycle.

To find this out we must find the angle (θ) of the waveform after 200µs.

$\theta = \frac{t}{P} \times 360^o$

$\theta = \frac{200\mu s}{500\mu s} \times 360^o$

$\theta = 144^o$

So, now that we know the angle at 200µs we can find the voltage at this time.

$v = V_{pk} \times Sin\theta$

$v = 9V_{pk} \times Sin144^o$

$v = 5.29V$

23. The meter doesn't tell us anything about the AC signal's shape.
It doesn't tell us anything about the signal's frequency.
It only reads the RMS value

Section 3

1. 0.5Vp-p square wave at 1kHz

2. To check whether the CRO inputs are calibrated.

   To explain, you can connect either of the CRO inputs to the *Calibration Output* signal and measure its voltage and period. If the CRO displays a signal that is not 0.5Vp-p and 1ms (the period of 1kHz) then the CRO is not calibrated.

   Also, if you're doing a practical exercise in class and you can't display a signal when you think there should be one you can use the *Calibration Output* to check where the problem might be. The procedure is as follows:

   - Set up the CRO per the notes on page 2-6 and connect the CRO input to the *Calibration output.*
   - If you don't get a squarewave on the display then replace the CRO's lead and repeat.
   - If you still don't get a display then the CRO is faulty. If you do get a display then the CRO lead was the problem.
   - Reconnect the CRO lead to the circuit. If you still don't get a signal then the circuit is wired incorrectly.

3. The *Horizontal Sweep* (*time/div*) control

4. The *Vertical Attenuation* (*volts/div*) control

5. The *Vertical Position* control

6. The *Trigger Level* control

7. The *Slope* control

8. The *Trigger Level* control

9. The *Auto-triggering* control

Section 3 (continued)

10.

Intensity: About half way round the knob's rotation.

Mode: Set to the channel that you're using (usually Channel 1 or Dual if you're using both channels).

Input Coupling: Set to the type of voltage you're measuring (usually AC but you would switch it to DC if you're measuring DC voltages).

Vertical Attenuator: Start off with it on 1V/div and adjust according to the size of the voltage you're measuring.

Vertical Attenuator Calibration: In the detent (locked) position.

Vertical Position: About half way round the knob's rotation.

Horizontal Sweep: Start off with it on 1ms/div and adjust according to the frequency of the signal you're measuring.

Horizontal Sweep Calibration: In the detent position

Horizontal Position: About half way round the knob's rotation.

Triggering Level: About half way round the knob's rotation and pulled out (to activate auto-triggering).

Sync:. "+"

Source: Channel 1.

11. (a)

Vp-p = $6\ divisions \times 2V/div = 12V$

Period = $5\ divisions \times 1ms/div = 5ms$

Frequency = $\frac{1}{P} = \frac{1}{5ms} = 200Hz$

(b)

Vp-p = $5.2\ divisions \times 0.5V/div = 2.6V$

Period = $4.4\ divisions \times 20ms/div = 88ms$

Frequency = $\frac{1}{P} = \frac{1}{88ms} = 11.36Hz$

Section 3 (continued)

11. (c)

Vp-p = 5.2 $divisions \times 50mV/div = 260mV$

Period = 5 $divisions \times 0.5\mu s/div = 2.5\mu s$

Frequency = $\frac{1}{P} = \frac{1}{2.5\mu s} = 400kHz$

12. (a)

Vertical Attenuator = 20mV/div

Horizontal timebase = 0.5μs/div

(b)

Vertical Attenuator = 5V/div

Horizontal timebase = 50μs/div

(c)

Vertical Attenuator = 50mV/div

Horizontal timebase = 5ms/div

13. Figure 15 shows the better way to view the signal when making voltage measurements. Doing so will give more accurate measurements (because the resolution has improved).

14. Figure 17 shows the better way to view the signal when making time measurements. Doing so will give more accurate measurements (because the resolution has improved).

Section 4

1. The *phase relationship* between signals is a reference to whether or not the signals cross the zero line heading toward the positive peak at the same time. If they do then the signals are said to be in phase. If they don't then the signals are said to be out of phase.

2. 0°

3. > 0° but < 360°

4. None of the above

5. 180°

6. 90°

7. Signal A - because it crosses the zero line (or reaches the peak) on the left of Signal B.

8. A phasor diagram is one that shows AC electrical quantities as rotating lines.

9. Rotating anti-clockwise.

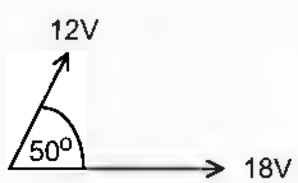
10. Signal B - because, as the signals are rotating anti-clockwise, it will cross the 0° point first.

11.

12.

13. Peak

14.



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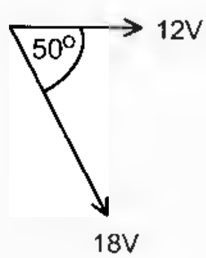
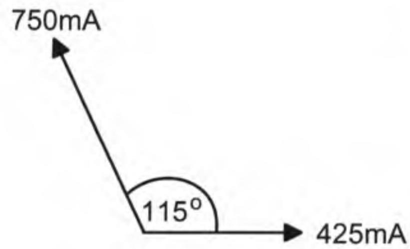


Section 4 (continued)

15.



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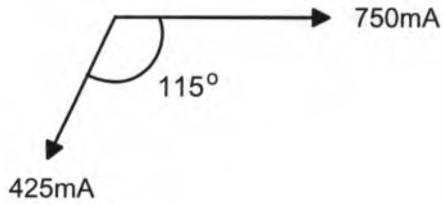
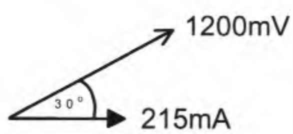


16.

Note: $70V_{RMS} = 98.9V_P$ and $240V_{RMS} = 339.4V_P$

17.



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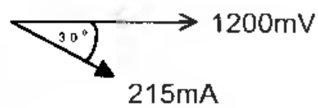

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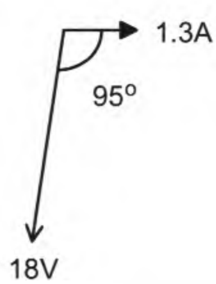


OR

Section 4 (continued)

19.

20.

Section 5

1. Mutual induction

2. Step-up

3. Step-down

4. All of the above (The power ratio is always 1 for these three transformers.)

5. They have losses.

6. Approximately 98% efficiency (that is, 2% of the input power doesn't reach the secondary)

7. Voltage ratio = $\frac{V_P}{V_S}$

   Voltage ratio = $\frac{240V}{15V}$

   Voltage ratio = 16

8. $N = \frac{N_P}{N_S}$

   $N = \frac{1800}{250}$

   $N = 7.2$

9. $V_S = \frac{V_P}{N}$

   $V_S = \frac{110V}{5.5}$

   $V_S = 20V$

10. As $V_S = \frac{V_P}{N}$ then:

    $V_P = V_S \times N$

    $V_P = 12V \times 18.33$

    $V_P = 220V$

Section 5 (continued)

11. $I_P = \frac{I_S}{N}$

$I_P = \frac{650mA}{45}$

$I_P = 14.44mA$

12. As $I_P = \frac{I_S}{N}$ then:

$I_S = I_P \times N$

$I_S = 125mA \times 13$

$I_S = 1.625A$

13. 2.2W Note: a calculation isn't necessary here because for step-up, step-down and one-to-one transformers the primary and secondary powers are equal.

14. $N = \frac{N_P}{N_S}$

$N = \frac{4}{1}$

$N = 4$

Therefore,

$V_S = \frac{V_P}{N}$

$V_S = \frac{120V_{p-p}}{4}$

$V_S = 30V_{p-p}$

15. $I_S = \frac{V_S}{R_S}$

$I_S = \frac{30V_{p-p}}{160\Omega}$

$I_S = 187.5mA_{p-p}$

Section 5 (continued)

16. $P = I_{S_{RMS}} \times V_{S_{RMS}}$ $I_{S_{RMS}} = 0.707 \times \frac{I_{S_{p-p}}}{2}$ $V_{S_{RMS}} = 0.707 \times \frac{V_{S_{p-p}}}{2}$

$P = 66.28mA \times 10.6V$ $I_{S_{RMS}} = 0.707 \times \frac{187.5A_{p-p}}{2}$ $V_{S_{RMS}} = 0.707 \times \frac{30V_{p-p}}{2}$

$P = 703mW$ $I_{S_{RMS}} = 66.28mA$ $V_{S_{RMS}} = 10.6V$

(Remember: AC power must be calculated using RMS values of voltage and current!)

17. $I_P = \frac{I_S}{N}$

$I_P = \frac{187.5mA_{p-p}}{4}$

$I_P = 46.88mA_{p-p}$

18. $P = I_{P_{RMS}} \times V_{P_{RMS}}$ $I_{P_{RMS}} = 0.707 \times \frac{I_{P_{p-p}}}{2}$ $V_{P_{RMS}} = 0.707 \times \frac{V_{P_{p-p}}}{2}$

$P = 16.57mA \times 42.42V$ $I_{P_{RMS}} = 0.707 \times \frac{46.88mA}{2}$ $V_{P_{RMS}} = 0.707 \times \frac{120V_{p-p}}{2}$

$P = 703mW$ $I_{P_{RMS}} = 16.57mA$ $V_{P_{RMS}} = 42.42V$

(Notice that the primary power is the same as the secondary power!)

19. $V_S = I_S \times R_L$

$V_S = 36.4mA \times 2k2\Omega$

$V_S = 80V$

20. $Voltage\ ratio = \frac{V_P}{V_S}$

$Voltage\ ratio = \frac{240V}{80V}$

$Voltage\ ratio = 3$ As turns ration and voltage ratio are the same…

$N_S = \frac{N_P}{N}$

$N_S = \frac{1400}{3}$

$N_S = 466.7$

Section 5 (continued)

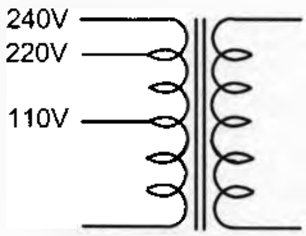
21. The same as the power in the secondary which is:

$P_S = I_S \times V_S$

$P_S = 36.4mA \times 80V$

$P_S = 2.91W$

22.



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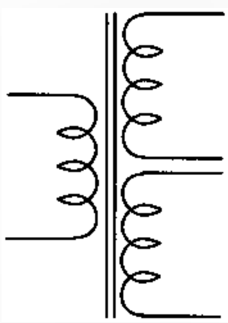

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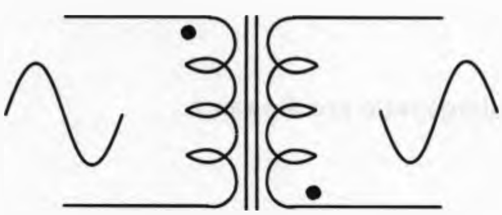


Section 6

1. One (There's only ever one current path in a series circuit regardless of whether the EMF is AC or DC.)
2. the same at every point around the circuit.
3. directly proportional to the resistor's value.
4. equal to the sum of the power dissipated by the individual resistors.
5. R1 and R2 have the same resistance.
6. the potential difference across R2 is greater than 5V.
7. the resistance of R1 is much bigger than R2.
8. the current through R2 is 100mA.
9. the same regardless of the resistor's value.
10. inversely proportional to the resistor's value.
11. equal to the sum of the power dissipated by the individual resistors.
12. R1 and R2 have the same resistance.
13. the resistance of R1 is smaller than R2.
14. the current through R2 is 1.5A.
15. 10V
16.
    (a) $79.42\mu A_{P\text{-}P}$
    (b) $14.3V_{P\text{-}P}$
    (c) $1.19V_{P\text{-}P}$
    (d) $6.51V_{P\text{-}P}$
    (e) $141.9\mu W$ (Remember, RMS values of V and I must be used for power calculations!)
    (f) $11.8\mu W$
    (g) $64.6\mu W$
    (h) $218.3\mu W$

Section 6 (continued)

17. Given that $P = I^2 \times R$ then $I = \sqrt{\frac{P}{R}}$. So,

$$I = \sqrt{\frac{400\mu W}{560k\Omega}}$$

$$I = 26.73\mu A$$

Once we know the circuit current, we can now find the potential difference across the two resistors:

$V_{R1} = I \times R1$	$V_{R2} = I \times R2$
$V_{R1} = 26.73\mu A \times 330k\Omega$	$V_{R2} = 26.73\mu A \times 560k\Omega$
$V_{R1} = 8.82V$	$V_{R2} = 14.97V$

Using Kirchhoff's Voltage Law we can find the supply voltage:

$$V_S = V_{R1} + V_{R2}$$

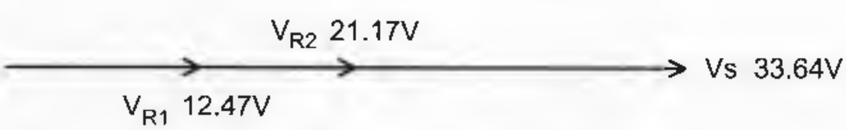
$$V_S = 8.82V + 14.97V$$

$$V_S = 23.79V$$

Using this information, we can find the peak-to-peak supply voltage:

$$V_S = 67.28V_{P-P}$$

18.



Note: remember that phasors use peak values.

Section 6 (continued)

19.

(a) $10.95mA_{P\text{-}P}$

(b) $6.25mA_{P\text{-}P}$

(c) $2.78mA_{P\text{-}P}$

(d) $1.92mA_{P\text{-}P}$

(e) 58.58mW

(f) 26mW

(g) 18mW

(h) 102.63mW

20. The peak-to-peak current through R2 can be calculated and is $231.9mA_{P\text{-}P}$

From this, the peak-to-peak supply voltage can be calculated and is $510.2V_{P\text{-}P}$

The current through R1 and R3 can be found next and are: $R1 = 510.2mA_{P-P}$ and $R3 = 108.5mA_{P-P}$

Finally, the total circuit current is equal to the sum of the branch currents which gives $850.6mA_{P\text{-}P}$.

21.

Note: remember that phasors use peak values.

22.

(a)

$I_T = 24.56\mu A_{P\text{-}P}$ (or $8.68\mu A_{RMS}$)

Section 6 (continued)

22 (b)

$I_{R1} = 24.56\mu A_{P\text{-}P}$ (or $8.68\mu A$)

$I_{R2} = 14.59\mu A_{P\text{-}P}$ (or $5.16\mu A$)

$I_{R3} = 9.97\mu A_{P\text{-}P}$ (or $3.52\mu A$)

$I_{R4} = 24.56\mu A_{P\text{-}P}$ (or $8.68\mu A$)

$I_{R5} = 21.91\mu A_{P\text{-}P}$ (or $7.74\mu A$)

$I_{R6} = 2.66\mu A_{P\text{-}P}$ (or $0.94\mu A$)

(c)

$V_{R1} = 8.1V_{P\text{-}P}$ (or $2.87V_{RMS}$)

$V_{R2} = 11.96V_{P\text{-}P}$ (or 4.23)

$V_{R3} = 11.96V_{P\text{-}P}$ (or 4.23)

$V_{R4} = 0.442V_{P\text{-}P}$ (or $156mV$)

$V_{R5} = 1.489V_{P\text{-}P}$ (or $526mV$)

$V_{R6} = 1.489V_{P\text{-}P}$ (or $526mV$)

(d)

$P_{R1} = 24.91\mu W$

$P_{R2} = 21.28\mu W$

$P_{R3} = 14.89\mu W$

$P_{R4} = 1.35\mu W$

$P_{R5} = 4.07\mu W$

$P_{R6} = 0.494\mu W$

Section 6 (continued)

23.

Note: remember that phasors use peak values.

24.

25.

26.

Section 7

1. Inductive reactance is the name given to the opposition to AC current due to the inductance of an inductor.

   [Think of it as being like AC resistance for inductors.]

2. Ohms.

3. lags the voltage across it by 90°.

4. Increase

5. Decrease — [This is Ohm's Law - if the circuit resistance increases, the current must decrease.]

6. Remain the same — [Remember, an inductor's inductance is only determined by things like length of wire, cross-sectional area, number of turns and core material.]

7. the current through it would double.

8. Increase

9. Capacitive reactance is the name given to the opposition to AC current due to the capacitance of a capacitor.

10. Ohms.

11. leads the voltage across the cap 90°.

12. Decrease

13. Increase

14. Remain the same — [Remember, a capacitor's capacitance is only determined by things like the cross-sectional area of the plates, the distance between them and the type of material used for the dielectric.]

15. Decrease

Section 7 (continued)

16. $X_L = 2\pi \times f \times L$

$X_L = 2\pi \times 40kHz \times 50mH$

$X_L = 12,566\Omega$

17. Given $X_L = 2\pi fL$ then

$f = \frac{X_L}{2\pi L}$

$f = \frac{8k\Omega}{2\pi \times 600\mu H}$

$f = 2.122MHz$

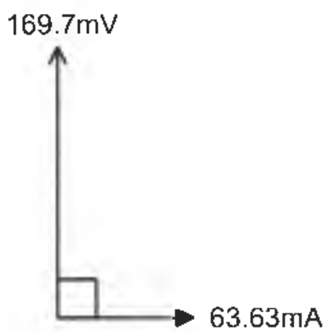
18. Given $X_L = 2\pi fL$ then

$L = \frac{X_L}{2\pi f}$

$L = \frac{103\Omega}{2\pi \times 50Hz}$

$L = 327.9mH$

19.



Section 7 (continued)

20. $X_C = \frac{1}{2\pi fC}$

$X_C = \frac{1}{2\pi \times 1.7MHz \times 820pF}$

$X_C = 114.2\Omega$

21. Given $X_C = \frac{1}{2\pi fC}$ then

$f = \frac{1}{2\pi X_C C}$

$f = \frac{1}{2\pi \times 11\Omega \times 180\mu F}$

$f = 80.4Hz$

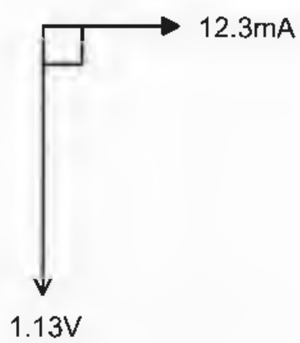
22. Given $X_C = \frac{1}{2\pi fC}$ then

$C = \frac{1}{2\pi f X_C}$

$C = \frac{1}{2\pi \times 100Hz \times 800\Omega}$

$C = 2\mu F$

23.



Section 8

1. Impedance is the total opposition to AC current provided by the combination of all the resistors, inductors and capacitors in a circuit.

2. Ohms.

3. Increase

4. Decrease

5. Remain the same

6. When V_S is a relatively low frequency

7. Decrease

8. Increase

9. Remain the same

10. When V_S is a relatively high frequency

11. Decrease until V_S reached the resonant frequency then increase

12. Increase until V_S reached the resonant frequency then decrease

13. At the resonant frequency

14. (a) 2149Ω

(b) $Z = \sqrt{R^2 + X_L^2}$

$Z = \sqrt{15k\Omega^2 + 2149\Omega^2}$

$Z = 15.15k\Omega$

15.

Section 8 (continued)

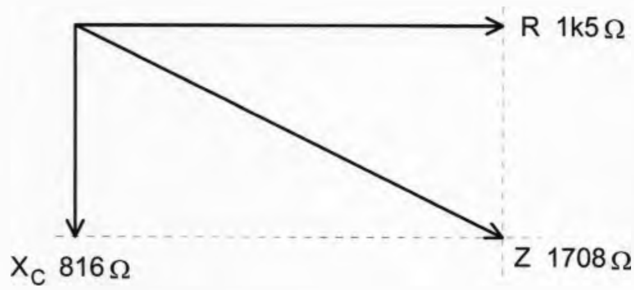
16. (a) 816Ω

(b) $Z = \sqrt{R^2 + X_C^2}$

$Z = \sqrt{1k5\Omega^2 + 816\Omega^2}$

$Z = 1708\Omega$

17.



18. (a) 1665Ω

(b) 159.2Ω

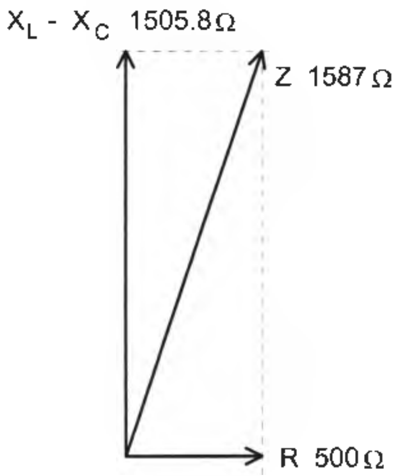
(c) $Z = \sqrt{R^2 + (X_L - X_C)^2}$

$Z = \sqrt{500\Omega^2 + (1665\Omega - 159.2\Omega)^2}$

$Z = 1587\Omega$

Section 8 (continued)

19.



Section 9

1. (a) 22kΩ

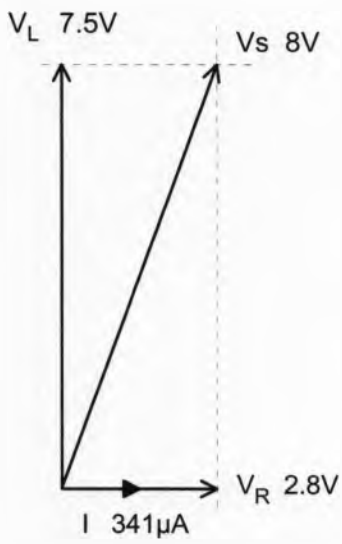
   (b) 23.5kΩ

   (c) $682\mu A_{P\text{-}P}$

   (d) $5.6V_{P\text{-}P}$

   (e) $15V_{P\text{-}P}$

2.



Note: remember that phasors use peak values.

3. (a) 7665Ω

   (b) $I = \frac{V_R}{R}$

   $I = \frac{4.2V_P}{12k\Omega}$

   $I = 350\mu A_P$

Section 9 (continued)

3. (c) $V_L = I \times X_L$

$V_L = 350\mu Ap \times 7665\Omega$

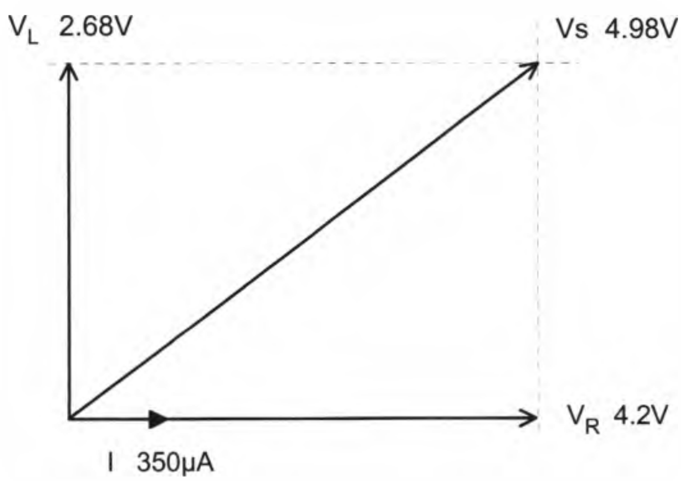
$V_L = 2.68V_P$

(d) $Vs = \sqrt{V_R^2 + V_L^2}$

$Vs = \sqrt{4.2V_P^2 + 2.68V_P^2}$

$Vs = 4.98V_P$

4.



5. (a) 226.2kΩ

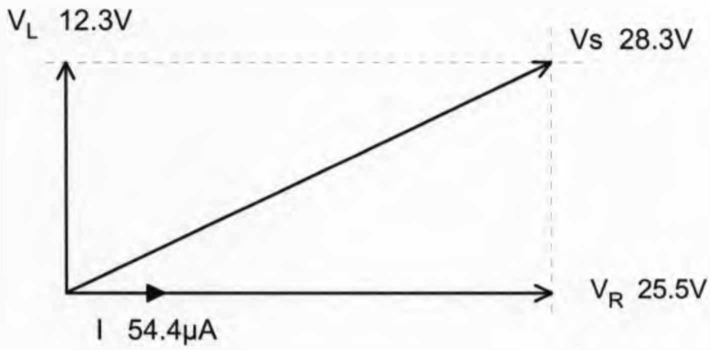
(b) 38.46μA

(c) 18V

(d) 20V

Section 9 (continued)

6.



Note: remember that phasors use peak values.

7. (a) 5.68Ω

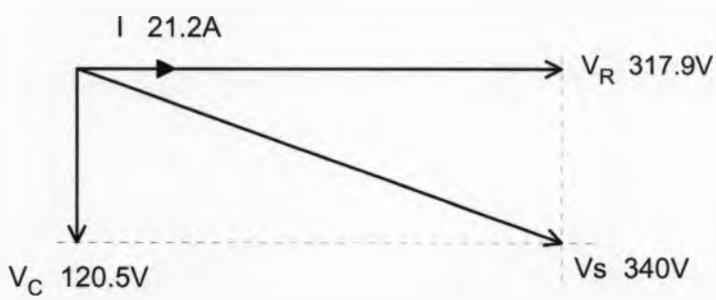
   (b) 16Ω

   (c) $21.2A_p$

   (d) $317.9V_p$

   (e) $120.5V_p$

8.



Section 9 (continued)

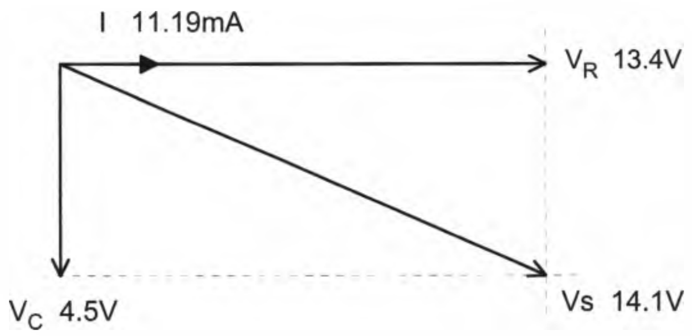
9. (a) 402Ω

 (b) 7.92mA

 (c) 3.18V

 (d) 10V

10.



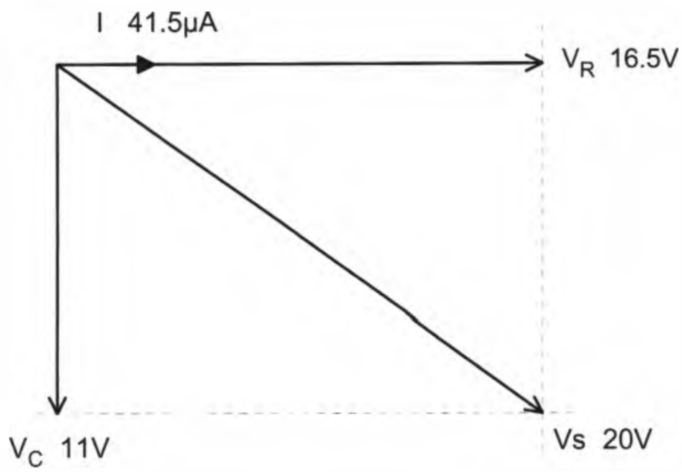
11. (a) 265.3kΩ

 (b) $82.9\mu A_{P\text{-}P}$

 (c) $33V_{P\text{-}P}$

 (d) $39.8V_{P\text{-}P}$

12.



Section 9 (continued)

13. (a) 2006Ω

(b) 2006Ω

(c) 3k9Ω

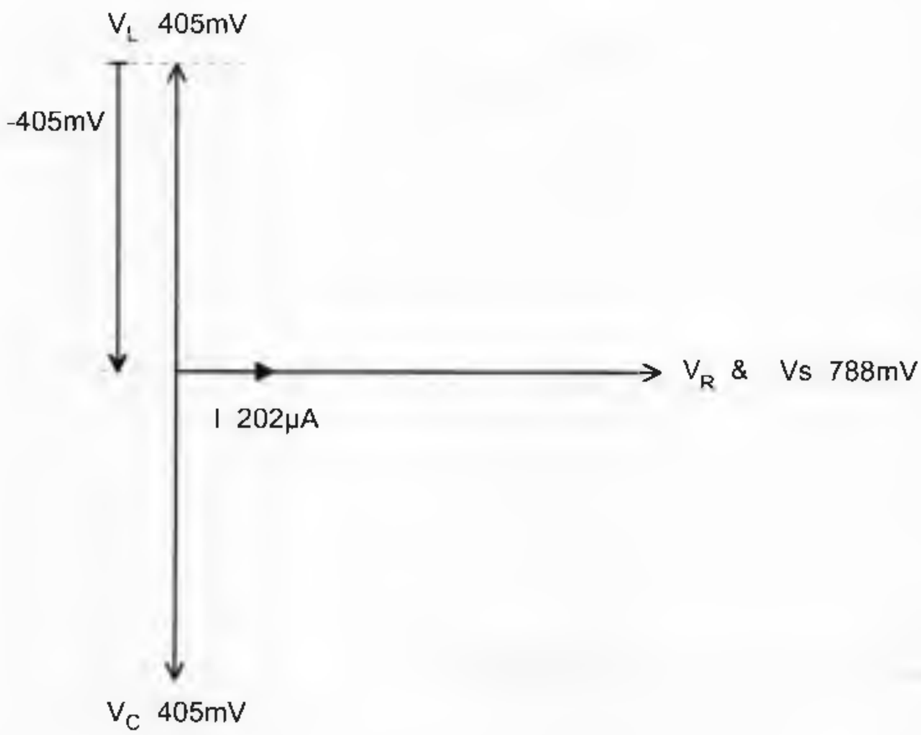
(d) 202μA_P

(e) 788mV_P

(f) 405mV_P

(g) 405mV_P

14.



Section 9 (continued)

15. (a) 471.2Ω

(b) 1061Ω

(c) $10mA_P$

(d) $4.7V_P$

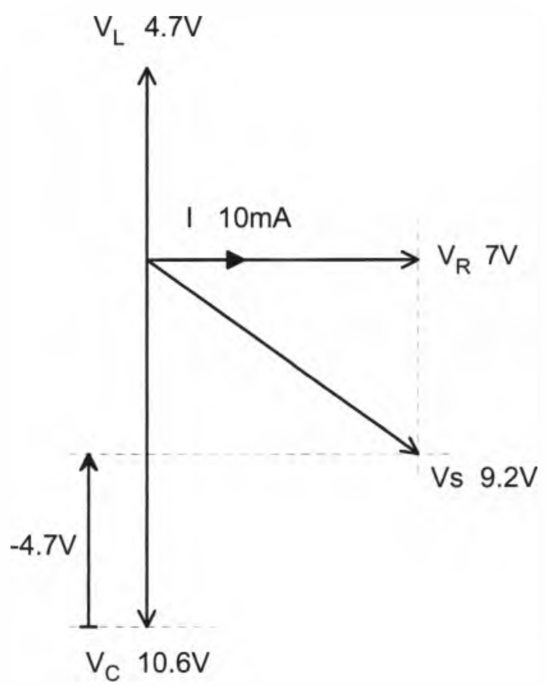
(e) $10.61V_P$

(f) $Vs = \sqrt{V_R^2 + (V_L - V_C)^2}$

$Vs = \sqrt{7V^2 + (4.7V - 10.61V)^2}$

$Vs = 9.16V_P$

16.



Section 9 (continued)

17. (a) 4146.9Ω

(b) 970.5Ω

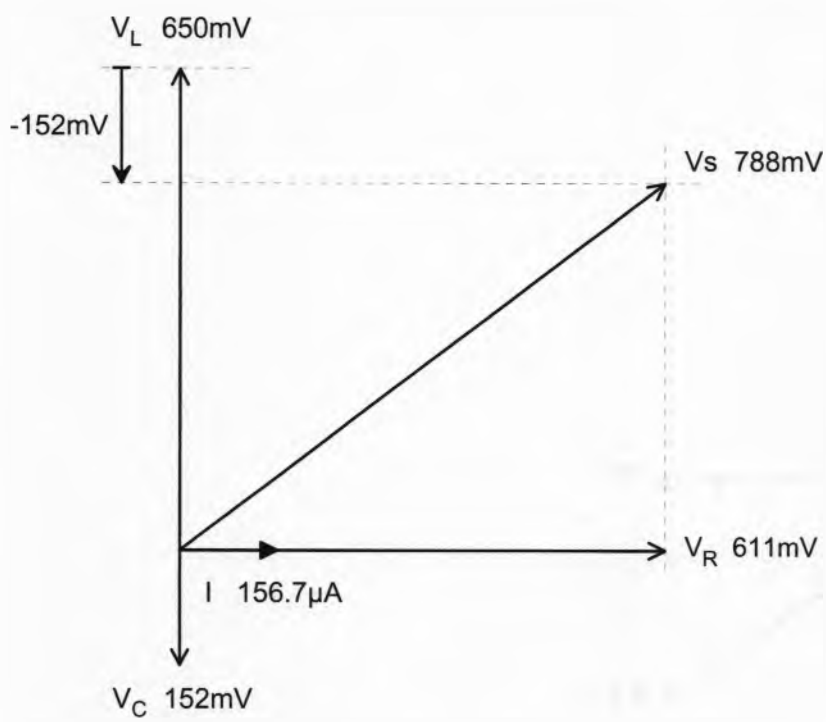
(c) $156.7\mu A_p$

(d) $611mV_p$

(e) $152.1mV_p$

(f) $788mV_p$

18.



Section 9 (continued)

19. (a) 207Ω

(b) $19{,}409\Omega$

(c) $19{,}594\Omega$

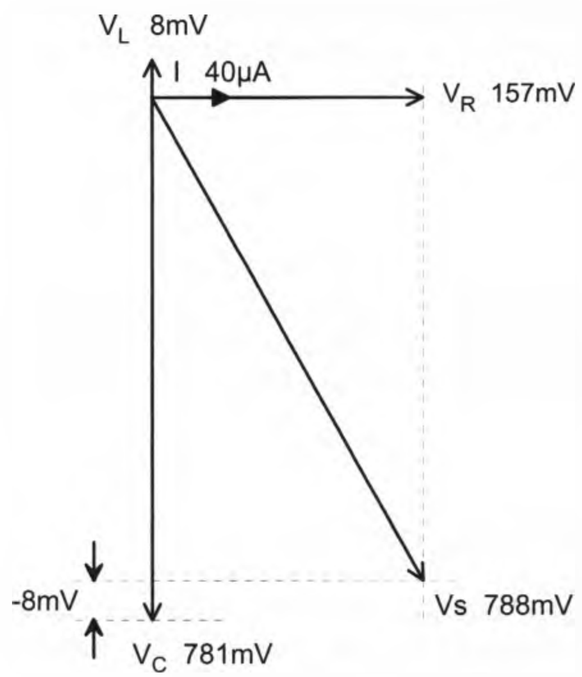
(d) $40.2\mu A_p$

(e) $156.8mV_p$

(f) $8.3mV_p$

(g) $780.6mV_p$

20.



Section 10

1. resistors only.

2. both capacitors and inductors.

3. The power is returned to the source during another part of the cycle.

4. watt (*W*).

5. volt-ampere reactive (*var*).

6. volt-ampere (*VA*).

7. Once the circuit current reaches the peak and begins to drop, the electromagnetic field about the inductor collapses. This induces a current in the circuit relieving the source of having to provide some or all of the circuit current during this time. In this way, the source saves power and so power is effectively transferred back to it.

8. Once the circuit current reaches the peak and begins to drop, the capacitor discharges returning stored electrons to the circuit as a current. Again, this current relieves the source of having to provide some or all of the circuit current during this time and so the source saves power.

9. real to apparent power.

10. a capacitor across inductive loads.

    [Note: Power factor correction can also involve connecting an inductor across capacitive loads. However, it "typically" involves connecting a capacitor across inductive loads because the loads of power distribution systems are much more likely to be inductive.]

11. apparent power.

12. reduce the source current without changing the load's real power.

    [Note: You may have been tempted to answer "increase the circuit's efficiency". However, power factor correction doesn't change the circuit's efficiency - assuming the inductor and capacitor are ideal. Remember, the reactive components return their power to the source and so they don't introduce any losses to the circuit.]

Section 10 (continued)

13. $X_C = \frac{1}{2\pi fC}$

$X_C = \frac{1}{2\pi \times 50Hz \times 250\mu F}$

$X_C = 12.73\Omega$

14. $Z = \sqrt{R^2 + X_C^2}$

$Z = \sqrt{25\Omega^2 + 12.73\Omega^2}$

$Z = 28.05\Omega$

15. $I = \frac{E}{Z}$

$I = \frac{100V}{28.05\Omega}$ [Note: The source voltage is specified in RMS already.]

$I = 3.56A$

16. $P = P_R = I^2 \times R$

$P = 3.56A^2 \times 25\Omega$

$P = 317.6W$

17. $Q = I^2 \times X_C$

$Q = 3.56A^2 \times 12.73\Omega$

$Q = 161.3\ vars$

18. $S = I \times V$ Or $S = I^2 \times Z$

$S = 3.56A \times 100V$ $S = 3.56^2 \times 28.05\Omega$

$S = 356VA$ $S = 355.5VA$

Section 10 (continued)

19. $pf = \frac{P}{S}$

$pf = \frac{317.6W}{356VA}$

$pf = 0.892$

20. Leading

21. This question can be solved in one of two ways:

$P = I^2R$

$I = \sqrt{\frac{P}{R}}$

$I = \sqrt{\frac{1175W}{45\Omega}}$

$I = 5.11A$

$S = I \times V$

$S = 5.11A \times 300V$

$S = 1533VA$

Or

$S = \sqrt{P^2 + Q^2}$

$S = \sqrt{1175W^2 + 984\ vars^2}$

$S = 1532.6VA$